or through some other intermediate means. Then the machine code is modified before being loaded and executed. A still further such technique is to convert the original code to an intermediate representation, which is thus modified and subsequently converted into machine code.

5   The present invention encompasses all such modification routes and also a combination of two, three or even more, of such routes.

FINALIZATION
10   Turning again to FIG. 14, there is illustrated a schematic representation of a single prior art computer operated as a JAVA virtual machine. In this way, a machine (produced by any one of various manufacturers and having an operating system operating in any one of various different languages) can operate in the particular language of the application program code 50, in this instance the JAVA language. That is, a JAVA virtual machine
15   72 is able to operate application code 50 in the JAVA language, and utilize the JAVA architecture irrespective of the machine manufacturer and the internal details of the machine.

         When implemented in a non-JAVA language or application code environment, the
20   generalized platform, and/or virtual machine and/or machine and/or runtime system is able to operate application code 50 in the language(s) (possibly including for example, but not limited to any one or more of source-code languages, intermediate-code languages, object-code languages, machine-code languages, and any other code languages) of that platform, and/or virtual machine and/or machine and/or runtime
25   system environment, and utilize the platform, and/or virtual machine and/or machine and/or runtime system and/or language architecture irrespective of the machine manufacturer and the internal details of the machine. It will also be appreciated in light of the description provided herein that the platform and/or runtime system may include virtual machine and non-virtual machine software and/or firmware architectures, as well
30   as hardware and direct hardware coded applications and implementations.

         Furthermore, when there is only a single computer or machine 72, the single machine of FIG. 14 is able to easily keep track of whether the specific objects 50X, 50Y, and/or 50Z are, liable to be required by the application code 50 at a later point of
35   execution of the application code 50. This may typically be done by maintaining a "handle count" or similar count or index for each object and/or class. This count may typically keep track of the number of places or times in the executing application code 50 where reference is made to a specific object (or class). For a handle count (or other count or index based) implementation that increments the handle count (or index) upward when
40   a new reference to the object or class is created or assigned, and decrements the handle count (or index) downward when a reference to the object or class is destroyed or lost, when the object handle count for a specific object reaches zero, there is nowhere in the executing application code 50 which makes reference to the specific object (or class) for which the zero object handle count (or class handle count) pertains. For example, in the
45   JAVA language and virtual machine environment, a "zero object handle count" correlates to the lack of the existence of any references (zero reference count) which point to the specific object. The object is then said to be "finalizable" or exist in a finalizable state. Object handle counts (and handle counters) may be maintained for each object in an

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analogous manner so that finalizable or non-finalizable state of each particular or specific object may be known. Class handle counts (and class handle counters) may be maintained for each class in an analogous manner to that for objects so that finalizable or non-finalizable state of each particular or specific class may be known. Furthermore,
5   asset handle counts or counters may be maintained for each asset in an analogous manner to that for classes and objects so that finalizable or non-finalizable state of each particular or specific asset may be known.

Once this finalizable state has been achieved for an object (or class), the object (or
10   class) can be safely finalized. This finalization may typically include object (or class) deletion, removal, clean-up, reclamation, recycling, finalization or other memory freeing operation because the object (or class) is no longer needed.

Therefore, in light of the availability of these reference, pointer, handle count or
15   other class and object type tracking means, the computer programmer (or other automated or nonautomated program generator or generation means) when writing a program such as the application code 50 using the JAVA language and architecture, need not write any specific code in order to provide for this class or object removal, clean up, deletion, reclamation, recycling, finalization or other memory freeing operation. As there is only a
20   single JAVA virtual machine 72, the single JAVA virtual machine 72 can keep track of the class and object handle counts in a consistent, coherent and coordinated manner, and clean up (or carry out finalization) as necessary in an automated and unobtrusive fashion, and without unwanted behaviour for example erroneous, premature, supernumerary, or re-finalization operation such as may be caused by inconsistent and/or incoherent
25   finalization states or handle counts. In analogous manner, a single generalized virtual machine or machine or runtime system can keep track of the class and object handle counts (or equivalent if the machine does not specifically use "object" and "class" designations) and clean up (or carry out finalization) as necessary in an automated and unobtrusive fashion.
30
The automated handle counting system described above is used to indicate when an object (or class) of an executing application program 50 is no longer needed and may be 'deleted' (or cleaned up, or finalized, or reclaimed, or recycled, or other otherwise freed). It is to be understood that when implemented in 'non-automated memory
35   management' languages and architectures (such as for example 'non-garbage collected' programming languages such as C, C++, FORTRAN, COBOL, and machine-CODE languages such as x86, SPARC, PowerPC, or intermediate-code languages), the application program code 50 or programmer (or other automated or non-automated program generator or generation means) may be able to make the determination at what
40   point a specific object (or class) is no longer needed, and consequently may be 'deleted' (or cleaned up, or finalized, or reclaimed, or recycled). Thus, 'deletion' in the context of this invention is to be understood to be inclusive of the deletion (or cleaning up, or finalization, or reclamation, or recycling, or freeing) of objects (or classes) on 'non-automated memory management' languages and architectures corresponding to deletion,
45   finalization, clean up, recycling, or reclamation operations on those 'non-automated memory management' languages and architectures.

For a more general set of virtual machine or abstract machine environments, and for current and future computers and/or computing machines and/or information appliances or processing systems, and that may not utilize or require utilization of either classes and/or objects, the inventive structure, method, and computer program and computer program product are still applicable. Examples of computers and/or computing machines that do not utilize either classes and/or objects include for example, the x86 computer architecture manufactured by Intel Corporation and others, the SPARC computer architecture manufactured by Sun Microsystems, Inc and others, the PowerPC computer architecture manufactured by International Business Machines Corporation and others, and the personal computer products made by Apple Computer, Inc., and others. For these types of computers, computing machines, information appliances, and the virtual machine or virtual computing environments implemented thereon that do not utilize the idea of classes or objects, the terms 'class' and 'object' may be generalized for example to include primitive data types (such as integer data types, floating point data types, long data types, double data types, string data types, character data types and Boolean data types), structured data types (such as arrays and records) derived types, or other code or data structures of procedural languages or other languages and environments such as functions, pointers, components, modules, structures, references and unions.

However, in the arrangement illustrated in FIG. 8, (and also in FIGS. 31-33), a plurality of individual computers or machines M1, M2 .... Mn are provided, each of which are interconnected via a communications network 53 or other communications link and each of which individual computers or machines is provided with a modifier 51 (See FIG. 5) and realised or implemented by or in for example the distributed run-time system (DRT) 71 (See FIG. 8) and loaded with a common application code 50. The term common application program is to be understood to mean an application program or application program code written to operate on a single machine, and loaded and/or executed in whole or in part on the plurality of computers or machines M1, M2...Mn. Put somewhat differently, there is a common application program represented in application code 50, and this single copy or perhaps a plurality of identical copies are modified to generate a modified copy or version of the application program or program code, each copy or instance prepared for execution on the plurality of machines. At the point after they are modified they are common in the sense that they perform similar operations and operate consistently and coherently with each other. It will be appreciated that a plurality of computers, machines, information appliances, or the like implementing the features of the invention may optionally be connected to or coupled with other computers, machines, information appliances, or the like that do not implement the features of the invention.

In some embodiments, some or all of the plurality of individual computers or machines may be contained within a single housing or chassis (such as so-called "blade servers" manufactured by Hewlett-Packard Development Company, Intel Corporation, IBM Corporation and others) or implemented on a single printed circuit board or even within a single chip or chip set.

Essentially the modifier 51 or DRT 71, or other code modifying means is responsible for modifying the application code 50 so that it may execute clean up or other

memory reclamation, recycling, deletion or finalization operations, such as for example finalization methods in the JAVA language and virtual machine environment, in a coordinated, coherent and consistent manner across and between the plurality of individual machines M1, M2, ..., Mn. It follows therefore that in such a computing
5 environment it is necessary to ensure that the local objects and classes on each of the individual machines is finalized in a consistent fashion (with respect to the others).

It will be appreciated in light of the description provided herein that there are alternative implementations of the modifier 51 and the distributed run time 71. For
10 example, the modifier 51 may be implemented as a component of or within the distributed run time 71, and therefore the DRT 71 may implement the functions and operations of the modifier 51. Alternatively, the function and operation of the modifier 51 may be implemented outside of the structure, software, firmware, or other means used to implement the DRT 71. In one embodiment, the modifier 51 and DRT 71 are
15 implemented or written in a single piece of computer program code that provides the functions of the DRT and modifier. The modifier function and structure therefore maybe subsumed into the DRT and considered to be an optional component. Independent of how implemented, the modifier function and structure is responsible for modifying the executable code of the application code program, and the distributed run time function
20 and structure is responsible for implementing communications between and among the computers or machines. The communications functionality in one embodiment is implemented via an intermediary protocol layer within the computer program code of the DRT on each machine. The DRT may for example implement a communications stack in the JAVA language and use the Transmission Control Protocol/Internet Protocol
25 (TCP/IP) to provide for communications or talking between the machines. Exactly how these functions or operations are implemented or divided between structural and/or procedural elements, or between computer program code or data structures within the invention are less important than that they are provided.

30 In particular, whilst the application program code executing on one particular machine (say, for example machine M3) may have no active handle, reference, or pointer to a specific local object or class (i.e. a "zero handle count"), the same application program code executing on another machine (say for example machine M5) may have an active handle, reference, or pointer to the local similar equivalent object or class
35 corresponding to the 'un-referenced' local object or class of machine M3, and therefore this other machine (machine M5) may still need to refer to or use that object or class in future. Thus if the corresponding similar equivalent local object or class on each machine M3 and M5 were to be finalized (or otherwise cleaned-up by some other memory clean-up operation) in an independent and uncoordinated manner relative to other machine(s),
40 the behaviour of the object and application as a whole is undefined – that is, in the absence of coordinated, coherent, and consistent finalization or memory clean-up operations between machines M1...Mn, conflict, unwanted interactions, or other anomalous behaviour such as permanent inconsistency between local similar equivalent corresponding objects on machine M5 and machine M3 is likely to result. For example,
45 if the local similar equivalent object or class on machine M3 were to be finalized, such as by being deleted, or cleaned up, or reclaimed, or recycled, from machine M3, in an uncoordinated and inconsistent manner with respect to machine M5, then if machine M5 were to perform an operation on or otherwise use the local object or class corresponding

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to the now finalized similar equivalent local object on machine M3 (such operation being for example, in an environment with a memory updating and propagation means of FIGS. 9, 10, 11, 12, and 13, a write to (or try to write to) the similar equivalent local object on machine M5 or amendment to that particular object's value), then that operation (the
5   change or attempted change in value) could not be performed (propagated from machine M5) throughout all the other machines M1, M2...Mn since at least the machine M3 would not include the relevant similar equivalent corresponding particular object in its local memory, the object and its data, contents and value(s) having been deleted by the prior object clean-up or finalization or reclamation or recycling operation. Therefore,
10   even though one may contemplate machine M5 being able to write to the object (or class) the fact that it has already been finalized on machine M3 means that likely such a write operation is not possible, or at the very least not possible on machine M3.

Additionally, if an object of class on machine M3 were to be marked finalizable
15   and subsequently finalized (such as by being deleted, or cleaned up, or reclaimed, or recycled) whilst the same object on the other machines M1, M2...Mn were not also marked as finalizable, then the execution of the finalization (or deletion, or clean up, or reclamation, or recycling) operation of that object on machine M3 would be premature with respect to coordinated finalization operation between all machines M1, M2...Mn, as
20   machines other than M3 are not yet ready to finalize their local similar equivalent object corresponding to the particular object now finalized or finalizable by machine M3. Therefore were machine M3 to execute the cleanup or other finalization routine on a given particular object (or class), the cleanup or other finalization routine would preform the clean-up or finalization not just for that local object (or class) on machine M3, but
25   also for all similar equivalent local objects or classes (i.e. corresponding to the particular object or class to be cleaned-up or otherwise finalized) on all other machines as well.

Were such either these circumstance to happen, the behaviour of the equivalent object on the other machines M1, M2...Mn is undefined and likely to result in permanent
30   and irrecoverable inconsistency between machine M3 and machines M1, M2...Mn. Therefore, though machine M3 may independently determine an object (or class) is ready for finalization and proceed to finalize the specified object (or class), machine M5 may not have made the same determination as to the same similar equivalent local object (or class) being ready to be finalized, and therefore inconsistent behaviour will likely result
35   due to the deletion of one of the plurality of similar equivalent objects on one machine (eg, machine M3) but not on the other machine (eg, machine M5) or machines, and the premature execution of the finalization routine of the specified object (or class) by machine M3 and on behalf of all other machines M1,M2...Mn. At the very least operation of machine M5 as well as other machines in such as an above circumstance is
40   unpredictable and would likely lead to inconsistent results, such inconsistency potentially arising for example from, uncoordinated premature execution of the finalization routine and/or deletion of the object on one, or a subset of, machines but not others. Thus, the desirable result of achieving or providing consistent coordinated finalization operation (or other memory clean-up operation) as required for the simultaneous operation of the same
45   application program code on each of the plurality of machines M1, M2...Mn would not be achieved. Any attempt therefore to maintain identical memory contents with a memory updating and propagation means of FIGS. 9, 10, 11, 12, and 13, or even identical memory contents as to a particular or defined set of classes, objects, values, or other data, for each

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of the machines M1, M2, ..., Mn, as required for simultaneous operation of the same application program, would not be achieved given conventional schemes.

5   In order to ensure consistent class and object (or equivalent) finalizable status and finalization or clean up between and amongst machines M1, M2, ..., Mn, the application code 50 is analysed or scrutinized by searching through the executable application code 50 in order to detect program steps (such as particular instructions or instruction types) in the application code 50 which define or constitute or otherwise represent a finalization operation or routine (or other memory, data, or code clean up routine, or other similar

10   reclamation, recycling, or deletion operation). In the JAVA language, such program steps may for example comprise or consist of some part of, or all of, a "finalize()" method of an object, and optionally any other code, routine, or method related to a 'finalize()' method, for example by means of a method invocation from the body of the 'finalize()' method to a different method.

15

         This analysis or scrutiny may take place either prior to loading the application program, or during the application program code 50 loading procedure, or even after the application program code 50 loading procedure. It may be likened to an instrumentation, program transformation, translation, or compilation procedure in that the application

20   program may be instrumented with additional instructions, and/or otherwise modified by meaning-preserving program manipulations, and/or optionally translated from an input code language to a different code language (such as from source-code or intermediate-code language to machine language), and with the understanding that the term compilation normally involves a change in code or language, for example, from source to

25   object code or from one language to another language. However, in the present instance the term "compilation" (and its grammatical equivalents) is not so restricted and can also include or embrace modifications within the same code or language. For example, the compilation and its equivalents are understood to encompass both ordinary compilation (such as for example by way of illustration but not limitation, from source-code to object-

30   code), and compilation from source-code to source-code, as well as compilation from object-code to object-code, and any altered combinations therein. It is also inclusive of so-called "intermediary languages" which are a form of "pseudo object-code".

         By way of illustration and not limitation, in one embodiment, the analysis or

35   scrutiny of the application code 50 may take place during the loading of the application program code such as by the operating system reading the application code from the hard disk or other storage device or source and copying it into memory and preparing to begin execution of the application program code. In another embodiment, in a JAVA virtual machine, the analysis or scrutiny may take place during the class loading procedure of the

40   java.lang.ClassLoader loadClass method (e.g., "java.lang.ClassLoader.loadClass()").

         Alternatively, the analysis or scrutiny of the application code 50 may take place even after the application program code loading procedure, such as after the operating system has loaded the application code into memory, or optionally even after execution

45   of the application program code has started, such as for example after the JAVA virtual machine has loaded the application code into the virtual machine via the "java.lang.ClassLoader.loadClass()" method and optionally commenced execution.

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As a consequence, of the above described analysis or scrutiny, clean up routines are initially looked for, and when found or identified a modifying code is inserted so as to give rise to a modified clean up routine. This modified routine is adapted and written to abort the clean up routine on any specific machine unless the class or object (or in the more general case to be 'asset') to be deleted, cleaned up, reclaimed, recycled, freed, or otherwise finalized is marked for deletion by all other machines. There are several different alternative modes wherein this modification and loading can be carried out.

By way of illustration and not limitation, in one embodiment, the analysis or scrutiny of the application code 50 may take place during the loading of the application program code such as by the operating system reading the application code from the hard disk or other storage device and copying it into memory whilst preparing to begin execution of the application program. In another embodiment, in a JAVA virtual machine, the analysis or scrutiny may take place during the execution of the java.lang.ClassLoader loadClass (e.g., "java.lang.ClassLoader.loadClass()") method.

Alternatively, the analysis or scrutiny of the application code 50 may take place even after the application program code loading procedure such as after the operating system has loaded the application code into memory and even started execution, or after the java virtual machine has loaded the application code into the virtual machine via the "java.lang.ClassLoader.loadClass()" method. In other words, in the case of the JAVA virtual machine, after the execution of "java.lang.ClassLoader.loadclass()" has concluded.

Thus, in one mode, the DRT 71/1 on the loading machine, in this example Java Machine M1 (JVM#1), asks the DRT's 71/2, ..., 71/n of all the other machines M2, ..., Mn if the similar equivalent first object 50X on all machines, say, is utilized, referenced, or in-use (i.e. not marked as finalizable) by any other machine M2, ..., Mn. If the answer to this question is yes (that is, a similar equivalent object is being utilized by another one or more of the machines, and is not marked as finalizable and therefore not liable to be deleted, cleaned up, finalized, reclaimed, recycled, or freed), then the ordinary clean up procedure is turned off, aborted, paused, or otherwise disabled for the similar equivalent first object 50X on machine JVM#1. If the answer is no, (that is the similar equivalent first object 50X on each machine is marked as finalizable on all other machines with a similar equivalent object 50X) then the clean up procedure is operated (or resumed or continued, or commenced) and the first object 50X is deleted not only on machine JVM#1 but on all other machines M2...Mn with a similar equivalent object 50X. Preferably, execution of the clean up routine is allocated to one machine, such as the last machine M1 marking the similar equivalent object or class as finalizable. The execution of the finalization routine corresponding to the determination by all machines that the plurality of similar equivalent objects is finalizable, is to execute only once with respect to all machines M1...Mn, and preferably by only one machine, on behalf of all machines M1....Mn. Corresponding to, and preferably following, the execution of the finalization routine, all machines may then delete, reclaim, recycle, free or otherwise clean-up the memory (and other corresponding system resources) utilized by their local similar equivalent object.

Annexures C1, C2, C3, and C4 (also reproduced in part in Tables XVI, XVII, XVIII, and XIX below) are exemplary code listings that set forth the conventional and unmodified computer program software code (such as may be used in a single machine or computer environment) of a finalization routine of application program 50 (Annexure C1

5   and Table XVI), and a post-modification excerpt of the same synchronization routine such as may be used in embodiments of the present invention having multiple machines (Annexures C2 and C3 and Tables XVII and XVIII). Also the modified code that is added to the finalization routine is highlighted in bold text.

10   Annexure C1 is a before-modification excerpt of the disassembled compiled form of the finalize() method of the example.java application of Annexure C4. Annexure C2 is an after-modification form of Annexure C1, modified by FinalLoader.java of Annexure C7 in accordance with the steps of FIG. 22. Annexure C3 is an alternative after-modification form of Annexure C1, modified by FinalLoader.java of Annexure C7 in

15   accordance with the steps of FIG. 22. The modifications are highlighted in bold.

Annexure C4 is an excerpt of the source-code of the example.java application used in before/after modification excerpts C1-C3. This example application has a single finalization routine, the finalize() method, which is modified in accordance with this

20   invention by FinalLoader.java of Annexure C7.

Table XVI. Annexure C1- Typical prior art finalization for a single machine

```
Method finalize()
0 getstatic #9 <Field java.io.PrintStream out>
3 ldc #24 <String "Deleted...">
5 invokevirtual #16 <Method void println(java.lang.String)>
8 return
```

Table XVII. Annexure C2 - Finalization For Multiple Machines

```
Method finalize()
0 aload_0
1 invokestatic #3 <Method boolean isLastReference(java.lang.Object)>
4 ifne 8
7 return
8 getstatic #9 <Field java.io.PrintStream out>
11 ldc #24 <String "Deleted...">
13 invokevirtual #16 <Method void println(java.lang.String)>
16 return
```

25

Table XVIII. Annexure C3 - Finalization For Multiple Machines (Alternative)

```
Method finalize()
0 aload_0
1 invokestatic #3 <Method boolean isLastReference(java.lang.Object)>
4 ifne 8
7 return
```

```
8 getstatic #9 <Field java.io.PrintStream out>
11 ldc #24 <String "Deleted...">
13 invokevirtual #16 <Method void println(java.lang.String)>
16 return
```

Table XIX. Annexure C4 - Source-code of the example.java application used in before/after modification excerpts of Annexures C1-C3

```
import java.lang.*;

public class example{

   /** Finalize method. */
   protected void finalize() throws Throwable{

      // "Deleted..." is printed out when this object is garbaged.
      System.out.println("Deleted...");

   }
}
```

5   It is noted that the compiled code in the annexure and portion repeated in the table is taken from the source-code of the file "example.java" which is included in the Annexure C4. In the procedure of Annexure C1 and Table XVI, the procedure name "Method finalize()" of Step 001 is the name of the displayed disassembled output of the finalize method of the compiled application code "example.java". The method name 10 "finalize()" is the name of an object's finalization method in accordance with the JAVA platform specification, and selected for this example to indicate a typical mode of operation of a JAVA finalization method. Overall the method is responsible for disposing of system resources or to perform other cleanup corresponding to the determination by the garbage collector of a JAVA virtual machine that there are no more 15 references to this object, and the steps the "example.java" code performs are described in turn.

        First (Step 002), the JAVA virtual machine instruction "getstatic #9 <Field java.io.PrintStream out>" causes the JAVA virtual machine to retrieve the object 20 reference of the static field indicated by the CONSTANT_Fieldref_info constant_pool item stored in the 2nd index of the classfile structure of the application program containing this example finalize() method and results on a reference to a java.io.PrintStream object in the field to be placed (pushed) on the stack of the current method frame of the currently executing thread.

25   Next (Step 003), the JAVA virtual machine instruction "ldc #24 <String "Deleted...">" causes the JAVA virtual machine to load the String value "Deleted" onto the stack of the current method frame and results in the String value "Deleted" loaded onto the top of the stack of the current method frame.

30   Next (Step 004), the JAVA virtual machine instruction "invokevirtual #16 <Method void println(java.lang.String)>" causes the JAVA virtual machine to pop the

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topmost item off the stack of the current method frame and invoke the "println" method, passing the popped item to the new method frame as its first argument, and results in the "println" method being invoked.

Finally, the JAVA virtual machine instruction "return" (Step 005) causes the JAVA virtual machine to cease executing this finalize() method by returning control to the previous method frame and results in termination of execution of this finalize method.

As a result of these steps operating on a single machine of the conventional configurations in FIG. 1 and FIG. 2, the JAVA virtual machine can keep track of the object handle count in a consistent, coherent and coordinated manner, and in executing the finalize() method containing the println operation is able to ensure that unwanted behaviour (for example premature or supernumerary finalization operation such as execution of the finalize() method of a single 'example.java' object more than once) such as may be caused by inconsistent and/or incoherent finalization states or handle counts, does not occur. Were these steps to be carried out on the plurality of machines of the configurations of FIG. 5 and FIG. 8 with the memory update and propagation replication means of FIGS. 9, 10, 11, 12, and 13, and concurrently executing the application program code 50 on each one of the plurality of machines M1...Mn, the finalization operations of each concurrently executing application program occurrence on each of the one of the machines would be performed without coordination between any other of the occurrences on any other of the machine(s). Given the desirable result of consistent, coordinated and coherent finalization operation across a plurality of a machines, this prior art arrangement would fail to perform such consistent coordinated finalization operation across the plurality of machines, as each machine performs finalization only locally and without any attempt to coordinate their local finalization operation with any other similar finalization operation on any one or more other machines. Such an arrangement would therefore be susceptible to unwanted or other anomalous behaviour due to uncoordinated, inconsistent and/or incoherent finalization states or handle counts, and associated finalization operation. Therefore it is desirable to overcome this limitation of the prior art arrangement.

In the exemplary code in Table XVIII (Annexure C3), the code has been modified so that it solves the problem of consistent, coordinated finalization operation for a plurality of machines M1...Mn, that was not solved in the code example from Table XVI (Annexure C1). In this modified finalize() method code, an "aload_0" instruction is inserted before the "getstatic #9" instruction in order to be the first instruction of the finalize() method. This causes the JAVA virtual machine to load the item in the local variable array at index 0 of the current method frame and store this item on the top of the stack of the current method frame, and results in the object reference of the 'this' object at index 0 being pushed onto the stack.

Furthermore, the JAVA virtual machine instruction "invokestatic #3 <Method boolean isLastReference(java.lang.Object)>" is inserted after the "0 aload_0" instruction so that the JAVA virtual machine pops the topmost item off the stack of the current method frame (which in accordance with the preceding "aload_0" instruction is a reference to the object to which this finalize() method belongs) and invokes the "isLastReference" method, passing the popped item to the new method frame as its first argument, and returning a boolean value onto the stack upon return from this

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"invokestatic" instruction. This change is significant because it modifies the finalize() method to execute the "isLastReference" method and associated operations, corresponding to the start of execution of the finalize() method, and returns a boolean argument (indicating whether the object corresponding to this finalize() method is the last
5   remaining reference amongst the similar equivalent object on each of the machines M1...Mn) onto the stack of the executing method frame of the finalize() method.

Next, two JAVA virtual machine instructions "ifne 8" and "return" are inserted into the code stream after the "1 invokestatic #3" instruction and before the "getstatic #9"
10   instruction. The first of these two instructions, the "ifne 8" instruction, causes the JAVA virtual machine to pop the topmost item off the stack and performs a comparison between the popped value and zero. If the performed comparison succeeds (i.e. if and only if the popped value is not equal to zero), then execution continues at the "8 getstatic #9" instruction. If however the performed comparison fails (i.e. if and only if the popped
15   value is equal to zero), then execution continues at the next instruction in the code stream, which is the "7 return" instruction. This change is particularly significant because it modifies the finalize() method to either continue execution of the finalize() method (i.e. instructions 8-16) if the returned value of the "isLastReference" method was positive (i.e. "true"), or discontinue execution of the finalize() method (i.e. the "7 return" instruction
20   causing a return of control to the invoker of this finalize() method) if the returned value of the "isLastReference" method was negative (i.e. "false").

The method void isLastReference(java.lang.Object), part of the FinalClient code of Annexure C5 and part of the distributed runtime system (DRT) 71, performs the
25   communications operations between machines M1...Mn to coordinate the execution of the finalize() method amongst the machines M1...Mn. The isLastReference method of this example communicates with the InitServer code of Annexure C6 executing on a machine X of FIG. 15, by means of sending an "clean-up status request" to machine X corresponding to the object being "finalized" (i.e. the object to which this finalize()
30   method belongs). With reference to FIG. 25 and Annexure C6, machine X receives the "clean-up status request" corresponding to the object to which the finalize() method belongs, and consults a table of clean-up counts or finalization states to determine the clean-up count or finalization state for the object to which the request corresponds.

35   If the plurality of similar equivalent objects one each one of the plurality of machines M1...Mn corresponding to the clean-up status request is marked for clean-up on all other machines than the requesting machine (i.e. n-1 machines), then machine X will send a response indicating that the plurality of similar equivalent objects are marked for clean-up on all other machines, and optionally update a record entry corresponding to
40   the specified similar equivalent objects to indicate the similar equivalent objects as now cleaned up. Alternatively, if the plurality of the similar equivalent objects corresponding to the clean-up status request is not marked for clean-up on all other machines than the requesting machine (i.e. less than n-1 machines), then machine X will send a response indicating that the plurality of similar equivalent objects is not marked for cleanup on all
45   other machines, and increment the "marked for clean-up counter" record (or other similar finalization record means) corresponding to the specified object, to record that the requesting machine has marked its one of the plurality of similar equivalent objects to be cleaned-up. Corresponding to the determination that the plurality of similar equivalent

objects to which this clean-up status request pertains is marked for clean-up on all other machines than the requesting machine, a reply is generated and sent to the requesting machine indicating that the plurality of similar equivalent objects is marked for clean-up on all other machines than the requesting machine. Additionally, and optionally, machine
5   X may update the entry corresponding to the object to which the clean-up status request pertained to indicate the plurality of similar equivalent objects as now "cleaned-up". Following a receipt of such a message from machine X indicating that the plurality of similar equivalent objects is marked for clean-up on all other machines, the isLastReference() method and operations terminate execution and return a 'true' value to
10 the previous method frame, which is the executing method frame of the finalize() method. Alternatively, following a receipt of a message from machine X indicating that the plurality of similar equivalent objects is not marked for clean-up on all other machines, the isLastReference() method and operations terminate execution and return "false" value to the previous method frame, which is the executing method frame of the finalize()
15 method. Following this return operation, the execution of the finalize() method frame then resumes as indicated in the code sequence of Annexure C3.

        It will. be appreciated that the modified code permits, in a distributed computing environment having a plurality of computers or computing machines, the coordinated
20 operation of finalization routines or other clean-up operations so that the problems associated with the operation of the unmodified code or procedure on a plurality of machines M1...Mn (such as for example erroneous, premature, multiple finalization, or re-finalization operation) does not occur when applying the modified code or procedure. It may be observed that the code in Annexure C2 and Table XVII is an alternative
25 but lesser preferred form of the code in Annexure C3. It is essentially functionally equivalent to the code and approach in Annexure C3.

        As seen in FIG. 15 a modification to the general arrangement of FIG. 8 is provided in that machines M1, M2, ..., Mn are as before and run the same application
30 code 50 (or codes) on all machines M1, M2, ..., Mn simultaneously or concurrently. However, the previous arrangement is modified by the provision of a server machine X which is conveniently able to supply housekeeping functions, for example, and especially the clean up of structures, assets and resources. Such a server machine X can be a low value commodity computer such as a PC since its computational load is low. As
35 indicated by broken lines in FIG. 15, two server machines X and X+1 can be provided for redundancy purposes to increase the overall reliability of the system. Where two such server machines X and X+1 are provided, they are preferably operated as redundant machines in a failover arrangement.

40   It is not necessary to provide a server machine X as its computational load can be distributed over machines M1, M2, ..., Mn. Alternatively, a database operated by one machine (in a master/slave type operation) can be used for the housekeeping function(s).

        FIG. 16 shows a preferred general procedure to be followed. After loading 161
45 has been commenced, the instructions to be executed are considered in sequence and all clean up routines are detected as indicated in step 162. In the JAVA language these are the finalization routines or finalize method (e.g., "finalize( )"). Other languages use different terms.

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Where a clean up routine is detected, it is modified at step 163 in order to perform consistent, coordinated, and coherent clean up or finalization across and between the plurality of machines M1, M2...Mn, typically by inserting further instructions into the

5   clean up routine to, for example, determine if the object (or class or other asset) containing this finalization routine is marked as finalizable across all similar equivalent local objects on all other machines, and if so performing finalization by resuming the execution of the finalization routine, or if not then aborting the execution of the finalization routine, or postponing or pausing the execution of the finalization routine

10   until such a time as all other machines have marked their similar equivalent local objects as finalizable. Alternatively, the modifying instructions could be inserted prior to the routine. Once the modification has been completed the loading procedure continues by loading modified application code in place of the unmodified application code, as indicated in step 164. Altogether, the finalization routine is to be executed only once,

15   and preferably by only one machine, on behalf of all machines M1...Mn corresponding to the determination by all machines M1...Mn that the particular object is finalizable.

FIG. 17 illustrates a particular form of modification. Firstly, the structures, assets or resources (in JAVA termed classes or objects) 50A, 50X...50Y which are possible

20   candidates to be cleaned up, are allocated a name or tag (for example a global name or tag), or have already been allocated a global name or tag, which can be used to identify corresponding similar equivalent local structures, assets, or resources (such as classes and objects in JAVA) globally on each of the machines M1, M2...Mn, as indicated by step 172. This preferably happens when the classes or objects are originally initialized. This

25   is most conveniently done via a table maintained by server machine X. This table also includes the "clean up status" of the class or object (or other asset). It will be understood that this table or other data structure may store only the clean up status, or it may store other status or information as well. In one embodiment, this table also includes a counter which stores a machine asset deletion count value identifying the number of machines

30   (and optionally the identity of the machines although this is not required) which have marked this particular object, class, or other asset for deletion. In one embodiment, the count value is incremented until the count value equals the number of machines. Thus a total machine asset deletion count value of less than (n-1), where n is the total number of machines in Mn indicates a "do not clean up" status for the object, class, or other asset as

35   a network (or machine constellation) whole, because the machine asset deletion count of less than n-1 means that one or more machines have yet to mark their similar equivalent local object (or class or other asset) as finalizable and that object cannot be cleaned up as unwanted or other anomalous behaviour may result. Stated differently, and by way of example but not limitation, if there are six machines and the asset deletion count is less

40   than five then it means that not all the other machines have attempted to finalize this object (i.e., not yet marked this object as finalizable), and therefore the object can't be finalised. If however the asset deletion count is five, then it means that there is only one machine that has yet to attempt to finalize this object (i.e., mark this object as finalizable) and therefore that last machine yet to mark the object as finalizable must be the current

45   machine attempting to finalize the object (i.e., marking the object as finalizable and consequently consulting the finalization table as to finalization status of this object on all other machines). In the configuration of six machines, the count value of n-1=5 means that five machines must have previously marked the object for deletion and the sixth

machine to mark this object for deletion is the machine that actually executes the full finalization routine.

As indicated in FIG. 17, if the global name or identifier is not marked for cleanup or deletion or other finalization on all other machines (i.e., all except on the machine proposing to carry out the clean up or deletion routine) then this means that the proposed clean up or finalization routine of the object or class (or other asset) should be aborted, stopped, suspend, paused, postponed, or cancelled prior to its initiation or if already initiated then to its completion if it has already begun execution, since the object or class is still required by one or more of the machines M1, M2…Mn, as indicated by step 175.

In one embodiment, the clean up or finalization routine is stopped from initiating or beginning execution; however, if some implementations it is difficult or practically impossible to stop the clean up or finalization routine from initiating or beginning execution. Therefore, in an alternative embodiment, the execution of the finalization routine that has already started is aborted such that it does not complete or does not complete in its normal manner. This alternative abortion is understood to include an actual abortion, or a suspend, or postpone, or pause of the execution of a finalization routine that has started to execute (regardless of the stage of execution before completion) and therefore to make sure that the finalization routine does not get the chance to execute to completion to clean up the object (or class or other asset), and therefore the object (or class or other asset) remains "uncleaned" (i.e., "unfinalised", or "not deleted").

However or alternatively, if the global name or other unique number or identifier for a plurality of similar equivalent local objects each on of the plurality of machines M1, M2…Mn is marked for deletion on all other machines, this means that no other machine requires the class or object (or other asset) corresponding to the global name or other unique number or identifier. As a consequence clean up routine and operation, or optionally the regular or conventional ordinary clean up routine and operation, indicated in step 176 can be, and should be, carried out.

FIG. 18 shows the enquiry made by the machine proposing to execute a clean up routine (one of M1, M2…Mn) to the server machine X. The operation of this proposing machine is temporarily interrupted, as shown in step 181 and 182, and corresponding to step 173 of FIG. 17. In step 181 the proposing machine sends an enquiry message to machine X to request the clean-up or finalization status of the object (or class or other asset) to be cleaned-up. Next, the proposing machine awaits a reply from machine X corresponding to the enquiry message sent by the proposing machine at step 181, indicated by step 182.

FIG. 25 shows the activity carried out by machine X in response to such a finalization or clean up status enquiry of step 181 in FIG. 18. The finalization or clean up status is determined as seen in step 192 which determines if the object (or class or other asset) corresponding to the clean-up status request of global name, as received at step 191 (191A), is marked for deletion on all other machines other than the enquiring machine 181 from which the clean-up status request of step 191 originates. The singular term object or class as used in this document (or the equivalent term of asset, or resource used in step 192 (192A) and other Figures) are to be understood to be inclusive of all similar equivalent objects (or classes, or assets, or resources) corresponding to the same global

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name on each of the plurality of machines M1, M2, ..., Mn. If the step 193 (193A)
determination is made that determines that the global named resource is not marked
("No") for deletion on (n-1) machines (i.e. is utilized elsewhere), then a response to that
effect is sent to the enquiring machine 194 (194A) but the "marked for deletion" counter
is incremented by one (1), as shown by step 197 (197A). Similarly, if the answer to this
determination is marked for deletion ("Yes") indicating that the global named resource is
marked for deletion on all other machines other than the waiting enquiring machine 182
then a corresponding reply is sent to the waiting enquiring machine 182 from which the
clean-up status request of step 191 originated as indicated by step 195 (195A). The
waiting enquiring machine 182 is then able to respond accordingly, such as for example
by: (i) aborting (or pausing, or postponing) execution of the finalization routine when the
reply from machine X of step 182 indicated that the similar equivalent local objects on
the plurality of machines M1, M2, ..., Mn corresponding to the global name of the object
proposed to be finalized of step 172 is still utilized elsewhere (i.e., not marked for
deletion on all other machines other than the machine proposing to carry out finalization);
or (ii) by continuing (or resuming, or starting) execution of the finalization routine when
the reply from machine X of step 182 indicated that the similar equivalent local objects
on the plurality of machines M1, M2...Mn corresponding to the global name of the object
proposed to be finalized of step 172 are not utilized elsewhere (i.e., marked for deletion
on all other machines other than the machine proposing to carry out finalization). As
indicated by broken lines in FIG. 25, preferably in addition to the "yes" response shown
in step 195, the shared table or cleaned-up statuses stored or maintained on machine X is
updated so that the status of the globally named asset is changed to "cleaned up" as
indicated by step 196.

Reference is made to the accompanying Annexure C in which: Annexure C1 is a
typical code fragment from an unmodified finalize routine, Annexure C2 is an equivalent
in respect of a modified finalize routine, and Annexure C3 is an alternative equivalent in
respect of a modified finalize routine.

Annexures C1 and C2/C3 repeated as Tables XVI and XVII/XVIII are the before
(pre-modification or unmodified code) and after (or post-modification or modified code)
excerpt of a finalization routine respectively. The modified code that is added to the
method is highlighted in bold. In the original code sample of Annexure C1, the finalize
method prints "Deleted..." to the computer console on event of finalization (i.e. deletion)
of this object. Thus, without management of object finalization in a distributed
environment, each machine would re-finalize the same object, thus executing the finalize
method more than once for a single globally-named coherent plurality of similar
equivalent objects. Clearly this is not what the programmer or user of a single
application program code instance expects to happen.

So, taking advantage of the DRT, the application code 50 is modified as it is
loaded into the machine by changing the clean-up, deletion, or finalization routine or
method. It will be appreciated that the term finalization is typically used in the context of
the JAVA language relative to the JAVA virtual machine specification existent at the date
of filing of this specification. Therefore, finalization refers to object and/or class cleanup
or deletion or reclamation or recycling or any equivalent form of object, class, asset or
resource clean-up in the more general sense. The term finalization should therefore be

taken in this broader meaning unless otherwise restricted.   The changes made (highlighted in bold) are the initial instructions that the finalize method executes. These added instructions check if this particular object is the last remaining object of the plurality of similar equivalent objects on the plurality of machines M1, M2...Mn to be
5   marked as finalizable, by calling a routine or procedure to determine the clean-up status of the object to be finalized, such as the "isLastReference()" procedure or method of a DRT 71 performing the steps of 172-176 of FIG. 17 where the determination as to the clean-up status of the particular object is sought, and which determines either a true result or a false result corresponding to whether or not this particular object on this particular
10 machine that is executing the determination procedure is the last of the plurality of machines M1, M2...Mn, each with one of a similar equivalent peer object, to request finalization. Recall that a peer object refers to a similar equivalent object on a different one of the machines, so that for example, in a configuration having eight machines, there will be eight peer objects (i.e. eight similar equivalent objects each on one of eight
15 machines).

        The finalization determination procedure or method "isLastReference()" of the DRT 71 can optionally take an argument which represents a unique identifier for this object (See Annexure C3 and Table XVIII). For example, the name of the object that is
20 being considered for finalization, a reference to the object in question being considered for finalization, or a unique number or identifier representing this object across all machines (or nodes), to be used in the determination of the finalization status of this object or class or other asset. This way, the DRT can support the finalization of multiple objects (or classes or assets) at the same time without becoming confused as to which of
25 the multiple objects are already finalized and which are not, by using the unique identifier of each object to consult the correct record in the finalization table referred to earlier.

        The DRT 71 can determine the finalization state of the object in a number of possible ways. Preferably, it (the requesting machine) can ask each other requested
30 machine in turn (such as by using a computer communications network to exchange query and response messages between the requesting machine and the requested machine(s) if their requested machine's similar equivalent object has been marked for finalization, and if any requested machine replies false indicating that their similar equivalent object is not marked for finalization, then return a false result at return from
35 the "isLastReference()" method indicating that the local similar equivalent object should not be finalized, otherwise return a true result at return from the "isLastReference()" method indicating that the local similar equivalent object can be finalized. Of course different logic schemes for true or false result may alternatively be implemented with the same effect. Alternatively, the DRT 71 on the local machine can consult a shared record
40 table (perhaps on a separate machine (e.g., machine X), or a coherent shared record table on each local machine and updated to remain substantially identical, or in a database) to determine if each of the plurality of similar equivalent objects have been marked for finalization by all requested machines except the current requesting machine.

45   If the "isLastReference()" method of the DRT 71 returns true then this means that this object has been marked for finalization on all other machines in the virtual or distributed computing environment (i.e. the plurality of machines M1...Mn), and hence, the execution of the finalize method is to proceed as this is considered the last remaining

similar equivalent object on the plurality of machines M1, M2...Mn to be marked or declared as finalizable.

On the other hand, if the "isLastReference()" method of the DRT 71 returns false, then this means that the plurality of similar equivalent objects has not been marked for finalization by all other machines in the distributed environment, as recorded in the shared record table on machine X of the finalization states of objects. In such a case, the finalize method is not to be executed (or alternatively resumed, or continued), as it will potentially invalidate the object on those machine(s) that are continuing to use their similar equivalent object and have yet to mark their similar equivalent object for finalization. Thus, when the DRT returns false, the inserted four instructions at the start of the finalize method prevent execution of the remaining code of the finalize method by aborting the execution of the finalize method through the use of a return instruction, and consequently aborting the Java Virtual Machine's finalization operation for this object.

Given the fundamental concept of testing to determine if a finalization, such as a deletion or clean up, is ready to be carried out on a class, object, or other asset; and if ready carrying out the finalization, and if not ready, then not carrying out the finalization, there are several different ways or embodiments in which this finalization concept, method, and procedure may be implemented.

In the first embodiment, a particular machine, say machine M2, loads the asset (such as class or object) inclusive of a clean up routine modifies it, and then loads each of the other machines M1, M3, ..., Mn (either sequentially or simultaneously or according to any other order, routine, or procedure) with the modified object (or class or asset) inclusive of the now modified clean up routine or routines. Note that there may be one or a plurality of routines corresponding to only one object in the application code or there can be a plurality of routines corresponding to a plurality of objects in the application code. Note that in one embodiment, the cleanup routine(s) that is (are) loaded is binary executable object code. Alternatively, the cleanup routine(s) that is (are) loaded is executable intermediate code.

In one arrangement, which may be termed "master/slave" (or primary/secondary) each of the slave (or secondary) machines M1, M3, ..., Mn loads the modified object (or class), and inclusive of the now modified clean-up routine(s), that was sent to it over the computer communications network or other communications link or path by the master (or primary) machine, such as machine M2, or some other machine such as a machine X of FIG. 15. In a slight variation of this "master/slave" or "primary/secondary" arrangement, the computer communications network can be replaced by a shared storage device such as a shared file system, or a shared document/file repository such as a shared database.

Note that the modification performed on each machine or computer need not and frequently will not be the same or identical. What is required is that they are modified in a similar enough way that in accordance with the inventive principles described herein, each of the plurality of machines behaves consistently and coherently relative to the other machines to accomplish the operations and objectives described herein. Furthermore, it will be appreciated in light of the description provided herein that there are a myriad of

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ways to implement the modifications that may for example depend on the particular hardware, architecture, operating system, application program code, or the like or different factors. It will also be appreciated that embodiments of the invention may be implemented within an operating system, outside of or without the benefit of any
5   operating system, inside the virtual machine, in an EPROM, in software, in firmware, or in any combination of these.

In a further variation of this "master/slave" or "primary/secondary" arrangement, machine M2 loads the asset (such as class or object) inclusive of a cleanup routine in
10   unmodified form on machine M2, and then (for example, M2 or each local machine) deletes the unmodified clean up routine that had been present on the machine in whole or part from the asset (such as class or object) and loads by means of a computer communications network the modified code for the asset with the now modified or deleted clean up routine on the other machines. Thus in this instance the modification is
15   not a transformation, instrumentation, translation or compilation of the asset clean up routine but a deletion of the clean up routine on all machines except one. In one embodiment, the actual code-block of the finalization or cleanup routine is deleted on all machines except one, and this last machine therefore is the only machine that can execute the finalization routine because all other machines have deleted the finalization routine.
20   One benefit of this approach is that no conflict arises between multiple machines executing the same finalization routine because only one machine has the routine.

The process of deleting the clean up routine in its entirety can either be performed by the "master" machine (such as machine M2 or some other machine such as machine X
25   of FIG. 15) or alternatively by each other machine M1, M3…Mn upon receipt of the unmodified asset. An additional variation of this "master/slave" or "primary/secondary" arrangement is to use a shared storage device such as a shared file system, or a shared document/file repository such as a shared database as means of exchanging the code for the asset, class or object between machines M1, M2…Mn and optionally a machine X of
30   FIG. 15.

In a still further embodiment, each machine M1, …, Mn receives the unmodified asset (such as class or object) inclusive of finalization or clean up routine(s), but modifies the routine(s) and then loads the asset (such as class or object) consisting of the now
35   modified routine(s). Although one machine, such as the master or primary machine may customize or perform a different modification to the finalization or clean up routine(s) sent to each machine, this embodiment more readily enables the modification carried out by each machine to be slightly different and to be enhanced, customized or optimized based upon its particular machine architecture, hardware, processor, memory,
40   configuration, operating system or other factors, yet still similar, coherent and consistent with other machines with all other similar modifications and characteristics that may not need to be similar or identical.

In a further arrangement, a particular machine, say M1, loads the unmodified asset
45   (such as class or object) inclusive of a finalization or clean up routine and all other machines M2, M3, …, Mn perform a modification to delete the clean up routine of the asset (such as class or object) and load the modified version.

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In all of the described instances or embodiments, the supply or communication of the asset code (such as class code or object code) to the machines M1, ..., Mn, and optionally inclusive of a machine X of FIG. 15 can be branched, distributed or communicated among and between the different machines in any combination or permutation; such as by providing direct machine to machine communication (for example, M2 supplies each of M1, M3, M4, etc directly), or by providing or using cascaded or sequential communication (for example, M2 supplies M1 which then supplies M3, which then supplies M4, and so on), or a combination of the direct and cascaded and/or sequential.

In a still further arrangement, the machines M1, ...,Mn, may send some or all load requests to an additional machine X (See for example the embodiment of FIG. 15), which performs the modification to the application program code 50 (such as consisting of assets, and/or classes, and/or objects) and inclusive of finalization or clean up routine(s), via any of the afore mentioned methods, and returns the modified application program code inclusive of the now modified finalization or clean-up routine(s) to each of the machines M1 to Mn, and these machines in turn load the modified application program code inclusive of the modified routine(s) locally. In this arrangement, machines M1 to Mn forward all load requests to machine X, which returns a modified application program code inclusive of modified finalization or clean-up routine(s) to each machine. The modifications performed by machine X can include any of the modifications covered under the scope of the present invention. This arrangement may of course be applied to some of the machines and other arrangements described herein before applied to other of the machines.

Persons skilled in the computing arts will be aware of various possible techniques that may be used in the modification of computer code, including but not limited to instrumentation, program transformation, translation, or compilation means.

One such technique is to make the modification(s) to the application code, without a preceding or consequential change of the language of the application code. Another such technique is to convert the original code (for example, JAVA language source-code) into an intermediate representation (or intermediate-code language, or pseudo code), such as JAVA byte code. Once this conversion takes place the modification is made to the byte code and then the conversion may be reversed. This gives the desired result of modified JAVA code.

A further possible technique is to convert the application program to machine code, either directly from source-code or via the abovementioned intermediate language or through some other intermediate means. Then the machine code is modified before being loaded and executed. A still further such technique is to convert the original code to an intermediate representation, which is thus modified and subsequently converted into machine code.

The present invention encompasses all such modification routes and also a combination of two, three or even more, of such routes.

SYNCHRONIZATION

Turning again to FIG. 14, there is illustrated a schematic representation of a single prior art computer operated as a JAVA virtual machine. In this way, a machine (produced by any one of various manufacturers and having an operating system operating in any one of various different languages) can operate in the particular language of the application program code 50, in this instance the JAVA language. That is, a JAVA virtual machine 72 is able to operate application code 50 in the JAVA language, and utilize the JAVA architecture irrespective of the machine manufacturer and the internal details of the machine.

When implemented in a non-JAVA language or application code environment, the generalized platform, and/or virtual machine and/or machine and/or runtime system is able to operate application code 50 in the language(s) (possibly including for example, but not limited to any one or more of source-code languages, intermediate-code languages, object-code languages, machine-code languages, and any other code languages) of that platform, and/or virtual machine and/or machine and/or runtime system environment, and utilize the platform, and/or virtual machine and/or machine and/or runtime system and/or language architecture irrespective of the machine manufacturer and the internal details of the machine. It will also be appreciated in light of the description provided herein that platform and/or runtime system may include virtual machine and non-virtual machine software and/or firmware architectures, as well as hardware and direct hardware coded applications and implementations.

Furthermore, the single machine (not a plurality of connected or coupled machines) of FIG. 14, or a more general virtual machine or abstract machine environment such as for example but not limited to an object-oriented virtual machine, is able to readily ensure that multiple different and potentially concurrent uses of specific objects 50X-50Z do not conflict or cause unwanted interactions, when specified by the use of mutual exclusion (e.g. "mutex") operators or operations (inclusive for example of locks, semaphores, monitors, barriers, and the like), such as for example by the programmer's use of a synchronizing or synchronization routine in a computer program written in the JAVA language. As each object exists singularly and only locally (that is locally within the machine within which execution is occurring) in this example, the single JAVA virtual machine 72 of FIG. 14 executing within this single machine is able to ensure that an object (or several objects) is (are) properly synchronized as defined by the JAVA Virtual Machine and Language Specifications existent at least as of the date of the filing of this patent application, when specified to do so by the application program (or programmer), and thus the object or objects to be synchronized are only utilized by one executing part of potentially multiple executing parts and potentially concurrently executing parts of the executable application code 50 at once or at the same time, such as for example potentially concurrently executing threads or processes. If another executing part and potentially concurrently executing part (such as for example but not limited to a potentially concurrently executing thread or process) of the executable application code 50 wishes to exclusively use the same object whilst that object is the subject of a mutual exclusion operation by a first executing part (e.g. a first thread or process), such as when a second executing part (e.g. a second thread or process) of a multiple part processing machine of FIG. 14 attempts to synchronize on a same object already synchronized by a first executing part, then the possible conflict is resolved by the JAVA virtual machine 72

such that the second and additional executing parts and potentially concurrently executing part or parts of the application program 50 have to wait until the first executing part has finished the execution of its synchronization routine or other mutual exclusion operation. It may be appreciated that in a conventional situation, a second or multiple executing part(s) (i.e. a second or multiple thread(s)) of the application program or program code may want to use the same object in a multiple-thread processing machine of FIG. 14.

For a more general set of virtual machine or abstract machine environments, and for current and future computers and/or computing machines and/or information appliances or processing systems, and that may not utilize or require utilization of either classes and/or objects, the inventive structure, method, and computer program and computer program product are still applicable. Examples of computers and/or computing machines that do not utilize either classes and/or objects include for example, the x86 computer architecture manufactured by Intel Corporation and others, the SPARC computer architecture manufactured by Sun Microsystems, Inc and others, the PowerPC computer architecture manufactured by International Business Machines Corporation and others, and the personal computer products made by Apple Computer, Inc., and others. For these types of computers, computing machines, information appliances, and the virtual machine or virtual computing environments implemented thereon that do not utilize the idea of classes or objects, the terms 'class' and 'object' may be generalized for example to include primitive data types (such as integer data types, floating point data types, long data types, double data types, string data types, character data types and Boolean data types), structured data types (such as arrays and records) derived types, or other code or data structures of procedural languages or other languages and environments such as functions, pointers, components, modules, structures, references and unions.

A similar procedure applies mutatis mutandis (that is, with suitable or necessary alterations) for classes 50A. In particular, the computer programmer (or if and when applicable, an automated or nonautomated computer program generator or generation means) when writing or generating a program using the JAVA language and architecture in a single machine, need only use a synchronization routine or routines in order to provide for this avoidance of conflict or unwanted interaction. Thus a single JAVA virtual machine can keep track of exclusive utilization of the classes and objects (or other asset) and avoid corresponding problems (such as conflict, race condition, unwanted interaction, or other anomalous behaviour due to unexpected critical dependence on the relative timing of events) as necessary in an unobtrusive fashion. The process whereby only one object or class ·is exclusively used is termed "synchronization" in the JAVA language. In the JAVA language, synchronization may usually be operationalized or implemented in one of three ways or means. The first way or means is through the use of a synchronization method description that is included in the source-code of an application program written in the JAVA language. The second way or means is by the inclusion of a 'synchronization descriptor' in the method descriptor of a compiled application program of the JAVA virtual machine. And the third way or means for performing synchronization are by the use of the instructions monitor enter (e.g., "monitorenter") and monitor exit (e.g., "monitorexit") of the JAVA virtual machine which signify respectively the beginning and ending of a synchronization routine which results in the acquiring or execution of a "lock" (or other mutual exclusion operator or operation), and the releasing

or termination of a "lock" (or other mutual exclusion operator or operation) respectively which prevents an asset being the subject of conflict (or race condition, or unwanted interaction, or other anomalous behaviour due to unexpected critical dependence on the relative timing of events) between multiple and potentially concurrent uses. An asset
5   may for example include a class or an object, as well as any other software /language/ runtime/ platform/ architecture or machine resource. Such resources may include for example, but are not limited to, software programs (such as for example executable software modules, subprograms, sub-modules, application program interfaces (API), software libraries, dynamically linkable libraries) and data (such as for example data
10   types, data structures, variables, arrays, lists, structures, unions), and memory locations (such as for example named memory locations, memory ranges, address space(s), registers), and input/output (I/O) ports and/or interfaces, or other machine, computer ,or information appliance resource or asset.

15   However, in the arrangement illustrated in FIG. 8, (and also in FIGS. 31-33), a plurality of individual computers or machines M1, M2, ..., Mn are provided, each of which are interconnected via a communications network 53 or other communications link and each of which individual computers or machines is provided with a modifier 51 (See in FIG. 5) and realised by or in for example the distributed run time (DRT) 71 (See FIG.
20   8) and loaded with a common application code 50. The term common application program is to be understood to mean an application program or application program code written to operate on a single machine, and loaded and/or executed in whole or in part on each one of the plurality of computers or machines M1, M2...Mn, or optionally on each one of some subset of the plurality of computers or machines M1, M2...Mn. Put
25   somewhat differently, there is a common application program represented in application code 50, and this single copy or perhaps a plurality of identical copies are modified to generate a modified copy or version of the application program, each copy or instance prepared for execution on the plurality of machines. At the point after they are modified they are common in the sense that they perform similar operations and operate
30   consistently and coherently with each other. It will be appreciated that a plurality of computers, machines, information appliances, or the like implementing the features of the invention may optionally be connected to or coupled with other computers, machines, information appliances, or the like that do not implement the features of the invention.

35   In some embodiments, some or all of the plurality of individual computers or machines may be contained within a single housing or chassis (such as so-called "blade servers" manufactured by Hewlett-Packard Development Company, Intel Corporation, IBM Corporation and others) or implemented on a single printed circuit board or even within a single chip or chip set.
40
            Essentially the modifier 51 or DRT 71 ensures that when an executing part (such as a thread or process) of the modified application program 50 running on one or more of the machines exclusively utilizes (e.g., by means of a synchronization routine or similar or equivalent mutual exclusion operator or operation) a particular local asset, such as an
45   objects 50X-50Z or class 50A, no other executing part and potentially concurrently executing part on machines M2...Mn exclusively utilizes the similar equivalent corresponding asset in its local memory at once or at the same time.

It will be appreciated in light of the description provided herein that there are alternative implementations of the modifier 51 and the distributed runtime system 71. For example, the modifier 51 may be implemented as a component of or within the distributed run time 71, and therefore the DRT 71 may implement the functions and operations of the modifier 51. Alternatively, the function and operation of the modifier 51 may be implemented outside of the structure, software, firmware, or other means used to implement the DRT 71. In one embodiment, the modifier 51 and DRT 71 are implemented or written in a single piece of computer program code that provides the functions of the DRT and modifier. The modifier function and structure therefore maybe subsumed into the DRT and considered to be an optional component. Independent of how implemented, the modifier function and structure is responsible for modifying the executable code of the application code program, and the distributed run time function and structure is responsible for implementing communications between and among the computers or machines. The communications functionality in one embodiment is implemented via an intermediary protocol layer within the computer program code of the DRT on each machine. The DRT may for example implement a communications stack in the JAVA language and use the Transmission Control Protocol/Internet Protocol (TCP/IP) to provide for communications or talking between the machines. Exactly how these functions or operations are implemented or divided between structural and/or procedural elements, or between computer program code or data structures within the invention are less important than that they are provided.

It will therefore be understood in light of the description provided here that the invention further includes any means of implementing thread-safety, regardless of whether it is through the use of locks (lock/unlock), synchronizations, monitors, semphafores, mutexes, or other mechanisms.

It will be appreciated that synchronization means or implies "exclusive use" or "mutual exclusion" of an asset or resource. Conventional structures and methods for implementations of single computers or machines have developed some methods for synchronization on such single computer or machine configurations. However, these conventional structures and methods have not provided solutions for synchronization between and among a plurality of computers, machines, or information appliances.

In particular, whilst one particular machine (say, for example machine M3) is exclusively using an object or class (or any other asset or resource), another machine (say, for example machine M5) may also be instructed by the code it is executing to exclusively use the local similar equivalent object or class corresponding to the similar equivalent object or class on machine M3 at the same time or an overlapping time period. Thus if the same corresponding local similar equivalent objects or classes on each machine M3 and M5 were to be exclusively used by both machines, then the behaviour of the object and application as a whole is undefined – that is, in the absence of proper exclusive use of an object (or class) when explicitly specified by the computer program (programmer), conflict, race conditions, unwanted interactions, anomalous behaviour due to unexpected dependence on the relative timing of events, or permanent inconsistency between the similar equivalent objects on machines M5 and M3 is likely to result. Thus the desirable result of achieving or providing consistent, coordinated, and coherent operation of synchronization routines (or other mutual exclusion operations) between and

amongst a plurality of machines, as required for the simultaneous and coordinated operation of the same application program code on each of the plurality of machines M1, M2...Mn, would not be achieved.

5   In order to ensure consistent synchronization between and amongst machines M1, M2...Mn the application code 50 is analysed or scrutinized by searching through the executable application code 50 in order to detect program steps (such as particular instructions or instruction types) in the application code 50 which define or constitute or otherwise represent a synchronization routine (or other mutual exclusion operation). In the JAVA language, such program steps may for example comprise or consist of an opening monitor enter (e.g. "monitorenter") instruction and one or more closing monitor exit (e.g. "monitorexit") instructions. In one embodiment, a synchronization routine may start with the execution of a "monitorenter" instruction and close with a paired execution of a "monitorexit" instruction.

15   This analysis or scrutiny of the application code 50 may take place either prior to loading the application program code 50, or during the application program code 50 loading procedure, or even after the application program code 50 loading procedure. It may be likened to an instrumentation, program transformation, translation, or compilation procedure in that the application code may be instrumented with additional instructions, and/or otherwise modified by meaning-preserving program manipulations, and/or optionally translated from an input code language to a different code language (such as for example from source-code language or intermediate-code language to object-code language or machine-code language), and with the understanding that the term compilation normally or conventionally involves a change in code or language, for example, from source code to object code or from one language to another language. However, in the present instance the term "compilation" (and its grammatical equivalents) is not so restricted and can also include or embrace modifications within the same code or language. For example, the compilation and its equivalents are understood to encompass both ordinary compilation (such as for example by way of illustration but not limitation, from source-code to object-code), and compilation from source-code to source-code, as well as compilation from object-code to object-code, and any altered combinations therein. It is also inclusive of so-called "intermediary languages" which are a form of "pseudo object-code".

35   By way of illustration and not limitation, in one embodiment, the analysis or scrutiny of the application code 50 may take place during the loading of the application program code such as by the operating system reading the application code from the hard disk or other storage device or source and copying it into memory and preparing to begin execution of the application program code. In another embodiment, in a JAVA virtual machine, the analysis or scrutiny may take place during the class loading procedure of the java.lang.ClassLoader loadClass method (e.g., "java.lang.ClassLoader.loadClass()").

45   Alternatively, the analysis or scrutiny of the application code 50 may take place even after the application program code loading procedure, such as after the operating system has loaded the application code into memory, or optionally even after execution of the application program code has started, such as for example after the JAVA virtual

machine has loaded the application code into the virtual machine via the "java.lang.ClassLoader.loadClass()" method and optionally commenced execution.

5   Reference is made to the accompanying Annexure D in which: Annexure D1 is a typical code fragment from a synchronization routine prior to modification (e.g., an exemplary unmodified synchronization routine), and Annexure D2 is the same synchronization routine after modification (e.g., an exemplary modified synchronization routine). These code fragments are exemplary only and other software code means for performing the modification in an exemplary language. It will be appreciated
10   that other software/firmware or computer program code may be used to accomplish the same or analogous function or operation without departing from the invention.

     Annexures D1 and D2 (also reproduced in part in Tables XX and XXI below) are exemplary code listings that set forth the conventional or unmodified computer program
15   software code (such as may be used in a single machine or computer environment) of a synchronization routine of application program 50 and a post-modification excerpt of the same synchronization routine such as may be used in embodiments of the present invention having multiple machines. The modified code that is added to the synchronization method is highlighted in bold text. Other embodiments of the invention
20   may provide for code or statements or instructions to be added, amended, removed, moved or reorganized, or otherwise altered.

     It is noted that the compiled code in the Annexure and portion repeated in the table is taken from the source-code of the file "example.java" which is included in the
25   Annexure D3. The disassembled compiled code that is listed in the Annexure and Table is taken from compiled source code of the file "EXAMPLE.JAVA". In the procedure of Annexure D1 and Table XX, the procedure name "Method void run()" of Step 001 is the name of the displayed disassembled output of the run method of the compiled application code of "example.java". The name "Method void run()" is arbitrary and selected for this
30   example to indicate a typical JAVA method inclusive of a synchronization operation. Overall the method is responsible for incrementing a memory location ("counter") in a thread-safe manner through the use of a synchronization statement and the steps to accomplish this are described in turn.

35   First (Step 002), the Java Virtual Machine instruction "getstatic #2 <Field java.lang.Object LOCK>" causes the Java Virtual Machine to retrieve the object reference of the static field indicated by the CONSTANT_Fieldref_info constant-pool item stored in the 2nd index of the classfile structure of the application program containing this example run() method and results in a reference to the object (hereafter
40   referred to as LOCK) in the field to be placed (pushed) on the stack of the current method frame of the currently executing thread.

     Next (Step 003), the Java Virtual Machine instruction "dup" causes the Java Virtual Machine to duplicate the topmost item of the stack and push the duplicated item
45   onto the topmost position of the stack of the current method frame and results in the reference to the LOCK object at the top of the stack being duplicated and pushed onto the stack.

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Next (Step 004), the Java Virtual Machine instruction "astore_1" causes the Java Virtual Machine to remove the topmost item of the stack of the current method frame and store the item into the local variable array at index 1 of the current method frame and results in the topmost LOCK object reference of the stack being stored in the local variable index 1.

Then (Step 005), the Java Virtual Machine instruction "monitorenter" causes the Java Virtual Machine to pop the topmost object off the stack of the current method frame and acquire an exclusive lock on said popped object and results in a lock being acquired on the LOCK object.

The Java Virtual Machine instruction "getstatic #3 <Field int counter>" (Step 006) causes the Java Virtual Machine to retrieve the integer value of the static field indicated by the CONSTANT_Fieldref_info constant-pool item stored in the 3rd index of the classfile structure of the application program containing this example run() method and results in the integer value of said field being placed (pushed) on the stack of the current method frame of the currently executing thread.

The Java Virtual Machine instruction "iconst_1" (Step 007) causes the Java Virtual Machine to load an integer value of "1" onto the stack of the current method frame and results in the integer value of 1 loaded onto the top of the stack of the current method frame.

The Java Virtual Machine instruction "iadd" (Step 008) causes the Java Virtual Machine to perform an integer addition of the two topmost integer values of the stack of the current method frame and results in the resulting integer value of the addition operation being placed on the top of the stack of the current method frame.

The Java Virtual Machine instruction "putstatic #3 <Field int counter>" (Step 009) causes the Java Virtual Machine to pop the topmost value off the stack of the current method frame and store the value in the static field indicated by the CONSTANT_Fieldref_info constant-pool item stored in the 3rd index of the classfile structure of the application program containing this example run() method and results in the topmost integer value of the stack of the current method frame being stored in the integer field named "counter".·

The Java Virtual Machine instruction "aload_1" (Step 010) causes the Java Virtual Machine to load the item in the local variable array at index 1 of the current method frame and store this item on the top of the stack of the current method frame and results in the object reference stored in the local variable array at index 1 being pushed onto the stack.

The Java Virtual Machine instruction "monitorexit" (Step 011) causes the Java Virtual Machine to pop the topmost object off the stack of the current method frame and release the exclusive lock on said popped object and results in the LOCK being released on the LOCK object.

Finally, the Java Virtual Machine instruction "return" (Step 012) causes the Java

Virtual Machine to cease executing this run() method by returning control to the previous method frame and results in termination of execution of this run() method.

As a result of these steps operating on a single machine of the conventional configurations in FIG. 1 and FIG. 2, the synchronization statement enclosing the increment operation of the "counter" memory location ensures that no two or more concurrently execution instances of this run() method will conflict, or otherwise result in unwanted interactions such as a race-condition or other anomalous behaviour due to unexpected critical dependence on the relative timing of the incrementing events performed of the one "counter" memory location. Were these steps to be carried out on the plurality of machines of the configurations of FIG. 5 and FIG. 8 with the memory update and propagation replication means of FIGS. 9, 10, 11, 12 and 13, and concurrently executing two or more instances or occurrences of the run() method each on a different one of the plurality of machines M1, M2...Mn, the mutual exclusion operations of each concurrently executing instance of the run() method would be performed on each corresponding one of the machines without coordination between those machines.

Given the desirable result of consistent coordinated synchronization operation across a plurality of machines, this prior art arrangement would fail to perform such consistent coordinated synchronization operation across the plurality of machines, as each machine performs synchronization only locally and without any attempt to coordinate their local synchronization operation with any other similar synchronization operation on any one or more other machines. Such an arrangement would therefore be susceptible to conflict or other unwanted interactions (such as race-conditions or other anomalous behaviour due to unexpected critical dependence on the relative timing of the "counter" increment events on each machine) between the machines M1, M2, ..., Mn. Therefore it is desirable to overcome this limitation of the prior art arrangement.

In the exemplary code in Table XXI (Annexure D2), the code has been modified so that it solves the problem of consistent coordinated synchronization operation for a plurality of machines M1, M2, ..., Mn, that was not solved in the code example from Table XX (Annexure D1). In this modified run() method code, a "dup" instruction is inserted between the "4 astore_1" and "6 monitorenter" instructions. This causes the Java Virtual Machine to duplicate the topmost item of the stack and push said duplicated item onto the topmost position of the stack of the current method frame and results in the reference to the LOCK object at the top of the stack being duplicated and pushed onto the stack.

Furthermore, the Java Virtual Machine instruction "invokestatic #23 <Method void acquireLock(java.lang.Object)>" is inserted after the "6 monitorenter" and before the "10 getstatic #3 <Field int counter>" statements so that the Java Virtual Machine pops the topmost item off the stack of the current method frame and invokes the "acquireLock" method, passing the popped item to the new method frame as its first argument. This change is particularly significant because it modifies the run() method to execute the "acquireLock" method and associated operations, corresponding to the "monitorenter" instruction preceding it.

Annexure D1 is a before-modification excerpt of the disassembled compiled form

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of the synchronization operation of example.java of Annexure D3, consisting of an
starting "monitorenter" instruction and ending "monitorexit" instruction. Annexure D2 is
an after-modification form of Annexure D1, modified by LockLoader.java of Annexure
D6 in accordance with the steps of FIG. 26. The modifications are highlighted in bold.

5

Table XX. Annexure D1

Step	Annexure D1
001	Method void run()
002	0 getstatic #2 <Field java.lang.Object LOCK>
003	3 dup
004	4 astore_1
005	5 monitorenter
006	6 getstatic #3 <Field int counter>
007	9 iconst_1
008	10 iadd
009	11 putstatic #3 <Field int counter>
010	14 aload_1
011	15 monitorexit
012	16 return

Table XXI. Annexure D2

Step	Annexure D2
001	Method void run()
002	0 getstatic #2 <Field java.lang.Object LOCK>
003	3 dup
004	4 astore_1
004A	**5 dup**
005	6 monitorenter
005A	**7 invokestatic #23 <Method void acquireLock(java.lang.Object)>**
006	10 getstatic #3 <Field int counter>
007	13 iconst_1
008	14 iadd
009	15 putstatic #3 <Field int counter>
010	18 aload_1
010A	**19 dup**
010B	**20 invokestatic #24 <Method void releaseLock(java.lang.Object)>**
011	23 monitorexit
	24 return

10   The method void acquireLock(java.lang.Object), part of the LockClient code of
Annexure D4 and part of the distributed runtime system (DRT) 71, performs the
communications operations between machines M1, ..., Mn to coordinate the execution of
the preceding "monitorenter" synchronization operation amongst the machines M1...Mn.
The acquireLock method of this example communicates with the LockServer code of
15 Annexure D5 executing on a machine X of FIG. 15, by means of sending an 'acquire lock

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request' to machine X corresponding to the object being 'locked' (i.e., the object corresponding to the "monitorenter" instruction), which in the context of Table XXI and Annexure D2 is the 'LOCK' object. With reference to FIG. 29, Machine X receives the

5   'acquire lock request' corresponding to the LOCK object, and consults a table of locks to determine the lock status corresponding to the plurality of similar equivalent objects on each of the machines, which in the case of Annexure D2 is the plurality of similar equivalent LOCK objects.

10   If all of the plurality of similar equivalent objects on each of the plurality of machines M1...Mn is presently not locked by any other machine M1...Mn, then Machine X will record the object as now locked and inform the requesting machine of the successful acquisition of the lock. Alternatively, if a similar equivalent object is presently locked by another one of the machines M1...Mn, then Machine X will append

15   this requesting machine to a queue of machines waiting to lock this plurality of similar equivalent objects, until such a time as machine X determines this requesting machine can acquire the lock. Corresponding to the successful acquisition of a lock by a requesting machine, a reply is generated and sent to the successful requesting machine informing that machine of the successful acquisition of the lock. Following a receipt of

20   such a message from Machine X confirming the successful acquisition of a requested lock, the acquireLock method and operations terminate execution and return control to the previous method frame, which is the context of Annexure D2 is the executing method frame of the run() method. Until such a time as the requesting machine receives a reply from machine X confirming the successful acquisition of the requested lock, the

25   operation of the acquireLock method and run() method are suspended until such a confirmatory reply is received. Following this return operation, the execution of the run() method then resumes. Exemplary source-code for an embodiment of the acquireLock method is provided in Annexure D4. Annexure D4 also provides additional detail concerning DRT 71 functionality.

30   Later, the two statements "dup" and "invokestatic #24 <Method void releaseLock(java.lang.Object)>" are inserted into the code stream after the "18 aload_1" statement and before the "23 monitorexit" statement. These two statements cause the Java Virtual Machine to duplicate the item on the stack and then invoke the releaseLock method with the topmost item of the stack as an argument to the method call and result in

35   the modification of the run() method to execute the "releaseLock" method and associated operations, corresponding to the following "monitorexit" instruction, before the procedure exits and returns.

The method void releaseLock(java.lang.Object), part of the LockClient code of Annexure D4 and part of the distributed runtime system (DRT) 71, performs the

40   communications operations between machines M1...Mn to coordinate the execution of the following "monitorexit" synchronization operation amongst the machines M1...Mn. The releaseLock method of this example communications with LockServer code of Annexure D5 executing on a machine X of FIG. 15, by means of sending a "release lock request" to machine X corresponding to the object being "unlocked" (i.e., the object

45   corresponding to the "monitorexit" instruction), which in the context of Table XXI and Annexure D2 is the 'LOCK' object. Corresponding to FIG. 30, machine X receives the "release lock request" corresponding to the LOCK object, and updates the table of locks to indicate the lock status corresponding to the plurality of similar equivalent 'LOCK'

objects as now "unlocked". Additionally, if there are other machines awaiting acquisition of this lock, then machine X is able to select one of the awaiting machines to be the new owner of the lock by updating the table of locks to indicate this selected one awaiting machine as the new lock owner, and informing the successful one of the awaiting

5   machines of its successful acquisition of the lock by means of a confirmatory reply. The successful one of the awaiting machines then resumes execution of its synchronization routine. Following the notification to machine X of lock release, the releaseLock method terminates execution and returns control to the previous method frame, which in this instance is the method frame of the run() method. Following this return operation, the

10   execution of the run() method resumes.

It will be appreciated that the modified code permits, in a distributed computing environment having a plurality of computers or computing machines, the coordinated operation of synchronization routines or other mutual exclusion operations between and

15   amongst machines M1...Mn so that the problems associated with the operation of the unmodified code or procedure on a plurality of machines M1...Mn (such as conflicts, unwanted interactions, race-conditions, or anomalous behaviour due to unexpected critical dependence on the relative time of events) does not occur when applying the modified code or procedure.

20

In the unmodified code sample of Annexure D1, the application program code includes instructions or operations that increment a memory location in local memory (used for a counter) within an enclosing synchronization routine. The purpose of the synchronization routine is to ensure thread-safety of the counter increment

25   operation in multi-threaded and multi-processing applications and computer systems. The terms thread-safe or thread-safety refer to code that is either re-entrant or protected from multiple simultaneous execution by some form of mutual exclusion. Multi-threaded applications in the context of the invention may, for example, include applications operating two or more threads of execution concurrently each on a different machine.

30   Thus, without the management of coordinated synchronization in environments comprising or consisting of a plurality of machines, each running concurrently executing part of a same application program, and with a memory updating and propagation replication means of FIGS. 9, 10, 11, 12, and 13, each computer or computing machine would perform synchronization in isolation, thus potentially incrementing the shared

35   counter at the same time, leading to potential conflicts or unwanted interactions such as race condition(s) and incoherent memory between the machines M1...Mn. It will be appreciated that although this embodiment is described using a shared counter, the use or provision of such shared counter or memory location is optional and not required for the synchronization aspects of the invention.   What is advantageous is that the

40   synchronization routine behaves in a manner as the programming language, runtime system, or machine architecture (or any combination thereof) guarantees – that is, stop two parts (for example, two threads) of the application program from executing the same synchronization routine or same mutual exclusion operation or operator concurrently. Clearly consistent, coherent and coordinated synchronization behaviour is what the

45   programmer or user of the application program code 50 expects to happen.

So, taking advantage of the DRT 71, the application code 50 is modified as it is loaded into the machine by changing the synchronization routine. It will be appreciated

in light of the description provided here that the modifications made on each machine may generally be similar in-so-far as they should advantageously achieve a consistent end result of coordinated synchronization operation amongst all the machines; however, given the broad applicability of the inventive synchronization method and associated

5   procedures, the nature of the modifications may generally vary without altering the effect produced. For example, in a simple variation, one or more additional instructions or statements may be inserted, such as for example a "no-operation" (nop) type instruction into the application will mean the modifications made are technically different, but the modified code still conforms to the invention. Embodiments of the invention may for

10   example, implement the changes by means of program transformation, translation, various forms of compilation, instrumentation, or by other means described herein or known in the art. The changes made (highlighted in bold text) are the starting or initial instructions and the ending instructions that the synchronization routine executes, and which correspond to the entry (start) and exit (finish) of the synchronization routine

15   respectively. These added instructions (or modified instruction stream) act to coordinate the execution of the synchronization routine amongst the multiple concurrently executing instances or occurrences of the modified run method executing on each one of, or some subset of, the plurality of machines M1...Mn, by invoking the acquireLock method corresponding to the start of execution of the synchronization routine, and by invoking

20   the releaseLock method corresponding to the finish of execution of the synchronization routine, thereby providing consistent coordinated operation of the synchronization routine (or other mutual exclusion operation or operator) as required for the simultaneous operation of the modified application program code that is running on or across the plurality of machines M1, M2,..., Mn. This also advantageously provides for operation

25   of the one application program in a coordinated manner across the machines.

        The acquire lock (e.g. "acquireLock()") method of the DRT 71 takes an argument "(java.lang.Object)" which represents a reference to (or some other unique identifier for) the particular local object for which the global lock is desired (See Annexure D2 and

30   Table XXI), and is to be used in acquiring a global lock across the plurality of similar equivalent objects on the other machines corresponding to the specified local object. The unique identifier may, for example be the name of the object, a reference to the object in question, or a unique number representing the plurality of similar equivalent objects across all nodes. By using a globally unique identifier across all connected machines to

35   represent the plurality of similar equivalent objects on the plurality of machines, the DRT can support the synchronization of multiple objects at the same time without becoming confused as to which of the multiple objects are already synchronized and which are not as might be the case if object (or class) identifiers were not unique, by using the unique identifier of each object to consult the correct record in the shared synchronization table.

40
        A further advantage of using a global identifier here is as a form of 'meta-name' for all the similar equivalent local objects on each one of the machines. For example, rather than having to keep track of each unique local name of each similar equivalent local object on each machine, one may instead define a global name (e.g.,

45   "globalname7787") which each local machine in turn maps to a local object (e.g., "globalname7787" points to object "localobject456" on machine M1, and "globalname7787" points to object "localobject885" on machine M2, and "globalname7787" points to object "localobject111" on machine M3, and so forth). It thereafter is easier to simply say "acquire

lock for globalname7787" which is then translated on machine 1 (M1) to mean "acquire
lock for localobject456", and is translated on machine 2 (M2) to mean "acquire lock for
localobject885", and so on.

5   The shared synchronization table that may optionally be used is a table, other
storage means, or any other data structure that stores an object (and/or class or other
asset) identifier and the synchronization status (or locked or unlocked status) of each
object (and/or class or other asset). The table or other storage means operates to relate an
object (and/or class or other asset, or a plurality of similar equivalent objects or classes or
10   assets) to a status of either locked or unlocked or some other physical or logical
indication of a locked state and an unlocked state. For example: the table (or any other
data structure one cares to employ) may advantageously include a named object identifier
and a record indicating if a named object (i.e., "globalname7787") is locked or unlocked.
In one embodiment, the table or other storage means stores a flag or memory bit, wherein
15   when the flag or memory bit stores a "0" the object is unlocked and when the flag or
memory bit stores a "1" the object is locked. Clearly, multiple bit or byte storage may be
used and different logic sense or indicators may be used without departing from the
invention.

20   The DRT 71 can determine the synchronization state of the object in any one of a
number of ways. Recall, for example that the invention may include any means of
implementing thread-safety, regardless of whether it is through the use of locks
(lock/unlock), synchronizations, monitors, semphafores, mutexes, or other mechanisms.
These means stop or limit concurrently executing parts of a single application program in
25   order to guarantee consistency according to the rules of synchronization, locks, or the
like. Preferably, it can ask each machine in turn if their local similar equivalent object (or
class or other asset or resource) corresponding to the object being sought to be locked is
presently synchronized, and if any machine replies true, then to pause execution of the
synchronization routine and wait until that presently synchronized similar equivalent
30   object on the other machine is unsynchronised, otherwise synchronize this object locally
and resume execution of the synchronization routine. Each machine may implement
synchronization (or mutual exclusion operations or operators) in its own way and this
may be different in the different machines. Therefore, although some exemplary
implementation details are provided, ultimately how synchronization (or mutual
35   exclusion operations) is (are) implemented, or precisely how synchronization or mutual
exclusion status (or locked/unlocked status) is recorded in memory or other storage
means, is not critical to the invention. By unsynchronized we generally mean unlocked
or otherwise not subject to a mutual exclusion operation, and by synchronized we
generally mean locked and subject to a mutual exclusion operation.

40
         Alternatively, the DRT 71 on each local machine can consult a shared record table
(perhaps on a separate machine (for example, on machine X which is different from
machines M1, M2, ..., Mn)), or can consult a coherent shared record table on each one of
the local machines, or a shared database established in a memory or other storage, to
45   determine if this object has been marked or identified as synchronized (or "locked") by
any machine and if so, then wait until the status of the object is changed to "unlocked"
and then acquire the lock on this machine, otherwise acquire the lock by marking the
object as locked (optionally by this machine) in the shared lock table.

In the situation where the shared record table is consulted, this may be considered as a variation of a shared database or data structure, where each machine has a local copy of a shared table (that is a replica of a shared table) with is updated to maintain coherency across the plurality of machines M1, ..., Mn.

In one embodiment, the shared record table refers to a shared table accessible by all machines M1, ..., Mn, that may for example be defined or stored in a commonly accessibly database such that any machine M1, ..., Mn can consult or read this shared database table for the locked or unlocked status of an object. A further alternative arrangement is to implement a shared record table as a table in the memory of an additional machine (which we call "machine X") which stores each object identification name and its lock status, and serves as the central repository which all other machines M1, ..., Mn consult to determine locked status of similar equivalent objects.

In any of these different alternative implementations, the manner in which a one of, or a plurality of, similar equivalent objects is marked or identified as being synchronized (or locked) or unsynchronized (or unlocked) is relatively unimportant, and various stored memory bits or bytes or flags may be utilized as are known in the art to identify either one of the two possible logic states. It will also be appreciated that in the present embodiment, that synchronized is largely synonymous with locked and unsynchronized is largely synonymous with unlocked. These same considerations apply for classes as well as for other assets or resources.

Recall that the DRT 71 is responsible for determining the locked status for an object (or class, or other asset, corresponding to a plurality of similar equivalent objects or classes or assets) seeking to be locked before allowing the synchronization routine corresponding to the acquisition of that lock to proceed. In the exemplary embodiment described here, the DRT consults the shared synchronization record table which in one embodiment resides on an special "machine X", and therefore the DRT needs to communicate via the network or other communications link or path with this machine X to enquire as to and determine the locked (or unlocked) status of the object (or class or other asset corresponding to a plurality of similar equivalent objects or classes or assets).

If the DRT on the local machine that is trying to execute a synchronization routine or other mutual exclusion operation determines that no other machine currently has a lock for this object (i.e., no other machine has synchronized this object) or any other one of a plurality of similar equivalent objects, then to acquire the lock for this object corresponding to the plurality of similar equivalent objects on all other machines, for example by means of modifying the corresponding entry in a shared table of locked states for the object sought to be locked or alternatively, sequentially acquiring the lock on all other similar equivalent objects on all other machines in addition to the current machine. Note that the intent of this procedure is to lock the plurality of similar equivalent objects (or classes or assets) on all the other machines M1, ..., Mn so that simultaneous or concurrent use of any similar equivalent objects by two or more machines is prevented, and any available approach may be utilized to accomplish this coordinated locking. For example, it does not matter if machine M1 instructs M2 to lock its similar equivalent local object, then instructs M3 to lock its similar equivalent local object, and then

instructs M4 and so on; or if M1 instructs M2 to lock its similar equivalent local object, and then M2 instructs M3 to lock its similar equivalent local object, and then M3 instructs M4 to lock its similar equivalent local object, and so forth, what is being sought is the locking of the similar equivalent objects on all other machines so that simultaneous or concurrent use any similar equivalent objects by two or more machines is prevented. Only once this machine has successfully confirmed that no other machine has currently locked a similar equivalent object, and this machine has correspondingly locked its locally similar equivalent object, can the execution of the synchronization routine or code-block begin.

On the other hand, if the DRT 71 within the machine about to execute a synchronization routine (such as machine M1) determines that another machine, such as machine M4 has already synchronized a similar equivalent object, then this machine M1 is to postpone continued execution of the synchronization routine (or code-block) until such a time as the DRT on machine M1 can confirm that no other machine (such as one of machines M2, M3, M4, or M5, ..., Mn) is presently executing a synchronize routine on a corresponding similar equivalent local object, and that this machine M1 has correspondingly synchronized its similar equivalent object locally. Recall that local synchronization refers to prior art conventional synchronization on a single machine, whereas global or coordinated synchronization refers to coordinated synchronization of, across and/or between similar equivalent local objects each on a one of the plurality of machines M1...Mn. In such a case, the synchronization routine (or code-block) is not to continue execution until this machine M1 can guarantee that no other machine M2, M3, M4, ..., Mn is executing a synchronization routine corresponding to the local similar equivalent object being sought to be locked, as it will potentially corrupt the object across the participating machines M1, M2, M3, ..., Mn due to susceptibility to conflicts or other unwanted interactions such as race-conditions, and the like problems resulting from the concurrent execution of synchronization routines. Thus, when the DRT determines that this object, or a similar equivalent object on another machine, is presently "locked", say by machine M4 (relative to all other machines), the DRT on machine M1 pauses execution of the synchronization routine by pausing the execution of the acquire lock (e.g., "acquireLock()") operation until such a time as a corresponding release lock (e.g., "releaseLock()") operation is executed by the present owner of the lock (e.g., machine M4).

Thus, on execution of a release lock (e.g. "releaseLock()") operation, the machine M4 which presently "owns" or holds a lock (i.e., is executing a synchronization routine) indicates the close of its synchronization routine, for example by marking this object as "unlocked" in the shared table of locked states, or alternatively, sequentially releasing locks acquired on all other machines. At this point, a different machine waiting to begin execution of a paused synchronization statement can then claim ownership of this now released lock by resuming execution of its postponed (i.e. delayed) "acquireLock()" operation, for example, by marking itself as executing a lock for this similar equivalent object in the shared table of synchronization states, or alternatively, sequentially acquiring local locks of similar equivalent objects on each of the other machines. It is to be understood that the resumed execution of the acquire lock (e.g., "acquireLock") operation is to be inclusive of the optional resumption of execution of the acquire lock (e.g., "acquireLock") method at the point that execution was paused, as well as the

alternative optional arrangement wherein the execution of the acquire lock (e.g., "acquireLock") operation is repeated so as to re-request the lock. Again, these same considerations also apply for classes and more generally to any asset or resource.

5   So, according to at least one embodiment and taking advantage of the operation of the DRT 71, the application code 50 is modified as it is loaded into the machine by changing the synchronization routine (consisting of at least a beginning "acquire lock" type instruction (such as a JAVA "monitorenter" instruction) and an ending "release lock" type instruction (such as a JAVA "monitorexit" instruction). "Acquire lock" type
10   instructions commence operation or execution of a mutual exclusion operation, generally corresponding to a particular asset such as a particular memory location or machine resource, and result in the asset corresponding to the mutual exclusion operation being locked with respect to some or all modes of simultaneous or concurrent use, execution or operation. "Release lock" type instructions terminate or otherwise discontinue operation
15   or execution of a mutual exclusion operation, generally corresponding to a particular asset such as a particular memory location or machine resource, and result in the asset corresponding to the mutual exclusion operation being unlocked with respect to some or all modes of simultaneous or concurrent use, execution or operation. The changes made (highlighted in bold) are the modified instructions that the synchronization routine
20   executes. These added instructions for example check if this lock has already been acquired by another machine. If this lock has not been acquired by another machine, then the DRT of this machine notifies all other machines that this machine has acquired the specified lock, and thereby stopping the other machines from executing synchronization routines corresponding to this lock.
25

The DRT 71 can determine and record the lock status of similar equivalent objects, or other corresponding memory location or machine or software resource on a plurality of machines, in many ways, such as for example, by way of illustration but not limitation:
30   1.   Corresponding to the entry to a synchronization routine by Machine M1, the DRT of machine M1 individually consults or communicates with each machine to ascertain if this global lock is already acquired by any other Machine M2, ..., Mn different from itself. If this global lock corresponding to this asset or object is or has already been acquired by another one of the machines M2, ..., Mn then the DRT of
35   Machine M1 pauses execution of the synchronization routine on machine M1 until all other machines no longer own a global lock on this asset or object (that is to say that none of the other machines any longer own a global lock corresponding to this asset or object), at which point machine M1 can successfully acquire the global lock such that all other machines M2, ..., Mn must now wait for machine M1 to release the global lock before a
40   different machine can in turn acquire it. Otherwise, when it is determined that this global lock corresponding to this asset or object has not already been acquired by another machine M2, ..., Mn the DRT continues execution of the synchronization routine, and such that all other machines M2, ..., Mn must now wait for machine M1 to release the global lock before a different machine can in turn acquire it.
45

Alternatively, 2.   Corresponding to the entry to a synchronization routine, the DRT consults a shared table of records (for example a shared database, or a copy of a shared table on each of the participating machines) which indicate if any machine

currently "owns" this global lock. If so, the DRT then pauses execution of the synchronization routine on this machine until no machine owns a global lock on a similar equivalent object. Otherwise the DRT records this machine in the shared table (or tables, if there are multiple tables of records, e.g., on multiple machines) as the owner of this global lock, and then continues executing the synchronization routine.

Similarly, when a global lock is released, that is to say, when the execution of a synchronization routine is to end, the DRT can "un-record", alter the status indicator, and/or reset the global lock status of machines in many alternative ways, for example by way of illustration but not limitation:

1.   Corresponding to the exit to a synchronization routine, the DRT individually notifies each other machine that it no longer owns the global lock.
Alternatively,

2.   Corresponding to the exit to a synchronization routine, the DRT updates the record for this globally locked asset or object (such as for example a plurality of similar equivalent objects or assets) in the shared table(s) of records such that this machine is no longer recorded as owning this global lock.

Still further, the DRT can provide an acquire global lock queue to queue machines needing to acquire a global lock in multiple alternative ways, for example by way of illustration but not limitation:

1.   Corresponding to the entry to a synchronization routine by Machine M1 say, the DRT of machine M1 notifies the present owning machine (say Machine M4) of the global lock that machine M1 would like to or needs to acquire the corresponding global lock upon release by the current owning machine in order to perform an operation. The specified machine M4, if there are no other waiting machines, then stores a record of the requesting machine's (i.e., machine M1) interest or request in a table or list, such that machine M4 may know subsequent to releasing the corresponding global lock that the machine M1 recorded in the table or list is waiting to acquire the same global lock, which, following the exit of the synchronization routine corresponding to the global lock held by machine M4, then notifies the waiting machine (i.e. machine M1) specified in the record of waiting machines, that the global lock can be acquired, and thus machine M1 can proceed to acquire the global lock and continue executing its own synchronization routine.

2.   Corresponding to the entry to a synchronization routine by machine M1 say, the DRT notifies the present owner of the global lock, say machine M4, that a specific machine (say machine M1) would like to acquire the lock upon release by that machine (i.e., machine M4). That machine M4, if it finds after consulting its records of waiting machines for this locked object, finds that there are already one or more other machines (say machines M2 and M7) waiting, then either appends machine M1 to the end of the list of machines M2 and M7 wanting to acquire this locked object, or alternatively, forwards the request from M1 to the first waiting machine (i.e., machine M2), or any other machine waiting (i.e., machine M7), which then, in turn, records machine M1 in their table or records of waiting machines.

In the example above, for example, the records may be kept on Machine M4 and store a queue or other ordered or indexed list of machines waiting to acquire the lock after Machine M4 releases the lock it holds. This list or queue may then be used or referenced by M4 so that M4 can pass the lock on to other machines in accordance with

the order of request or any other prioritization scheme. Alternatively, the list may be unordered, and machine M4 may pass the global lock on to any machine in the list or record.

5   3.   Corresponding to the entry to a synchronization routine, the DRT records itself in a shared table(s) of records (for example, a table stored in a shared database accessible by all machines, or multiple separate tables which are substantially similar).

Still further or in the alternative, the DRT 71 can notify other machines queued to acquire this global lock corresponding to the exit of a synchronization routine by this
10   machine in the following alternative ways, for example:

1.   Corresponding to the exit of a synchronization routine, the DRT notifies one of the awaiting machines (for example, this first machine in the queue of waiting machines) that the global lock is released,

2.   Corresponding to the exit of a synchronization routine, the DRT notifies
15   one of the awaiting machines (for example, the first machine in the queue of waiting machines) that the global lock is released, and additionally, provides a copy of the entire queue of machines (for example, the second machine and subsequent machines awaiting for this global lock). This way, the second machine inherits the list of waiting machines from the first machine, and thereby ensures the continuity of the queue of waiting
20   machines as each machine in turn down the list acquires and subsequently releases the same global lock.

During the abovementioned scrutiny, "monitorenter" and "monitorexit" instructions (or methods) are initially looked for and, when found, a modifying code is
25   inserted so as to give rise to a modified synchronization routine. This modified routine additionally acquires and releases the global lock. There are several different modes whereby this modification and loading can be carried out.

As seen in FIG. 15 a modification to the general arrangement of FIG. 8 is
30   provided in that machines M1, M2...Mn are as before and run the same application code 50 (or codes) on all machines M1....Mn simultaneously or concurrently. However, the previous arrangement is modified by the provision of a server machine X which is conveniently able to supply housekeeping functions, for example, and especially the synchronization of structures, assets, and resources. Such a server machine X can be a
35   low value commodity computer such as a PC since its computational load is low. As indicated by broken lines in FIG. 15, two server machines X and X+1 can be provided for redundancy purposes to increase the overall reliability of the system. Where two such server machines X and X+1 are provided, they are preferably but optionally operated as redundant machines in a failover arrangement.
40

It is not necessary to provide a server machine X as its computational load can be distributed over machines M1, M2...Mn. Alternatively, a database operated by one machine (in a master/slave type operation) can be used for the housekeeping function(s).

45   FIG. 16 shows a preferred general procedure to be followed. After loading 161 has been commenced, the instructions to be executed are considered in sequence and all synchronization routines are detected as indicated in step 162. In the JAVA language

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these are the "monitorenter" and "monitorexit" instructions, and methods marked as synchronized in the method descriptor. Other languages use different terms.

Where a synchronization routine is detected 162, it is modified in step 163 in order to perform consistent, coordinated, and coherent synchronization operation (or other mutual exclusion operation) across the plurality of machines M1...Mn, typically by inserting further instructions into the synchronization (or other mutual exclusion) routine to, for example, coordinate the operation of the synchronization routine amongst and between similar equivalent synchronization or other mutual exclusion operations on other one or more of the plurality of machines M1...Mn, so that no two or more machines execute a similar equivalent synchronization or other mutual exclusion operation at once or overlapping. Alternatively, the modifying instructions may be inserted prior to the routine, such as for example prior to the instruction(s) or operation(s) related to a synchronization routine. Once the modification step 163 has been completed the loading procedure continues by loading the modified application code in place of the unmodified application code, as indicated in step 164. The modifications preferably take the form of an "acquire lock on all other machines" operation and a "release lock on all other machines" modification as indicated at step 163.

FIG. 27 illustrates a particular form of modification. Firstly, the structures, assets or resources (in JAVA termed classes or objects eg 50A, 50X-50Y) or more generally "locks" to be synchronized have already been allocated a name or tag (for example a global name or tag) which can be used to identify corresponding similar equivalent local objects, or assets, or resources, or locks on each of the machines M1....Mn, as indicated by step 172. This preferably happens when the classes or objects are originally initialized. This is most conveniently done via a table maintained by server machine X. This table also includes the synchronization status of the class or object or lock. It will be understood that this table or other data structure may store only the synchronization status, or it may store other status or information as well. In the preferred embodiment, this table also includes a queue arrangement which stores the identities of machines which have requested use of this asset or lock.

As indicated in step 173 of FIG. 27, next an "acquire lock" request is sent to machine X, after which, the sending machine awaits for confirmation of lock acquisition as shown in step 174. Thus, if the global name is already locked (i.e. a corresponding similar local asset is in exclusive use by another machine other than the machine proposing to acquire the lock) then this means that the proposed synchronization routine of the corresponding object or class or asset or lock should be paused until the corresponding object or class or asset or lock is unlocked by the current owner.

Alternatively, if the global name is not locked, this means that no other machine is exclusively using a similar equivalent class, object, asset or lock, and confirmation of lock acquisition is received straight away. After receipt of confirmation of lock acquisition, execution of the synchronization routine is allowed to continue, as shown in step 175.

FIG. 28 shows the procedures followed by the application program executing machine which wishes to relinquish a lock. The initial step is indicated at step 181. The

operation of this proposing machine is temporarily interrupted by steps 183, 184 until the
reply is received from machine X, corresponding to step 184, and execution then resumes
as indicated in step 185. Optionally, and as indicated in step 182, the machine requesting
release of a lock is made to lookup the "global name" for this lock preceding a request
5   being made to machine X. This way, multiple locks on multiple machines may be
acquired and released without interfering with one another.

FIG. 29 shows the activity carried out by machine X in response to an "acquire
lock" enquiry (of FIG. 27). After receiving an "acquire lock" request at step 191, the
10   lock status is determined at steps 192 and 193 and, if no - the named resource is not free
or otherwise "locked", the identity of the enquiring machine is added at step 194 to (or
forms) the queue of awaiting acquisition requests. Alternatively, if the answer is yes - the
named resource is free and "unlocked" - the corresponding reply is sent at step 197. The
waiting enquiring machine is then able to execute the synchronization routine accordingly
15   by carrying out step 175 of FIG. 27. In addition to the yes response, the shared table is
updated at step 196 so that the status of the globally named asset is changed to "locked".

FIG. 30 shows the activity carried out by machine X in response to a "release
lock" request of FIG. 28. After receiving a "release lock" request at step 201, machine X
20   optionally, and preferably, confirms that the machine requesting to release the global lock
is indeed the current owner of the lock, as indicated in step 202. Next, the queue status is
determined at step 203 and, if no-one is waiting to acquire this lock, machine X marks
this lock as "unowned" (or "unlocked") in the shared table, as shown in step 207, and
optionally sends a confirmation of release back to the requesting machine, as indicated by
25   step 208. This enables the requesting machine to execute step 185 of FIG. 28.

Alternatively, if yes − that is, other machines are waiting to acquire this lock -
machine X marks this lock as now acquired by the next machine in the queue, as shown
in step 204, and then sends a confirmation of lock acquisition to the queued machine at
30   step 205, and consequently removes the new lock owner from the queue of waiting
machines, as indicated in step 206.

Given the fundamental concept of modifying the synchronization routines (or
other mutual exclusion operations or operators) to coordinate operation between and
35   amongst a plurality of machines M1....Mn, there are several different ways or
embodiments in which this coordinated, coherent and consistent synchronization (or other
mutual exclusion) operation concept, method, and procedure may be carried out and
implemented.

40   .   In the first embodiment, a particular machine, say machine M2, loads the asset
(for example a class or object) inclusive of a synchronization routine(s), modifies it, and
then loads each of the other machines M1, M3...Mn (either sequentially, or
simultaneously or according to any other order, routine, or procedure) with the modified
asset (or class or object) inclusive of the new modified synchronization routine(s). Note
45   that there may be one or a plurality of routine(s) corresponding to only one object in the
application code, or there may be a plurality of routines corresponding to a plurality of
objects in the application code. Note that in one embodiment, the synchronization

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routine(s) that is (are) loaded is binary executable object code. Alternatively, the synchronization routine(s) that is (are) loaded is executable intermediate code.

In this arrangement, which may be termed "master/slave" each of the slave (or secondary) machines M1, M3, ..., Mn loads the modified object (or class), and inclusive of the new modified synchronization routine(s), that was sent to it over the computer communications network or other communications link or path by the master (or primary) machine, such as machine M2, or some other machine such as a machine X of FIG. 15. In a slight variation of this "master/slave" or "primary/secondary" arrangement, the computer communications network can be replaced by a shared storage device such as a shared file system, or a shared document/file repository such as a shared database.

Note that the modification performed on each machine or computer need not and frequently will not be the same or identical. What is required is that they are modified in a similar enough way that in accordance with the inventive principles described herein, each of the plurality of machines behaves consistently and coherently relative to the other machines to accomplish the operations and objectives described herein. Furthermore, it will be appreciated in light of the description provided herein that there are a myriad of ways to implement the modifications that may for example depend on the particular hardware, architecture, operating system, application program code, or the like or different factors. It will also be appreciated that embodiments of the invention may be implemented within an operating system, outside of or without the benefit of any operating system, inside the virtual machine, in an EPROM, in software, in firmware, or in any combination of these.

In a further variation of this "master/slave" or "primary/secondary" arrangement, machine M2 loads asset (such as class or object) inclusive of an (or even one or more) synchronization routine in unmodified form on machine M2, and then (for example, machine M2 or each local machine) modifies the class (or object or asset) by deleting the synchronization routine in whole or part from the asset (or class or object) and loads by means of a computer communications network or other communications link or path the modified code for the asset with the now modified or deleted synchronization routine on the other machines. Thus in this instance the modification is not a transformation, instrumentation, translation or compilation of the asset synchronization routine but a deletion of the synchronization routine on all machines except one.

The process of deleting the synchronization routine in its entirety can either be performed by the "master" machine (such as machine M2 or some other machine such as machine X of FIG. 15) or alternatively by each other machine M1, M3, ..., Mn upon receipt of the unmodified asset. An additional variation of this "master/slave" or "primary/secondary" arrangement is to use a shared storage device such as a shared file system, or a shared document/file repository such as a shared database as means of exchanging the code (including for example, the modified code) for the asset, class or object between machines M1, M2,..., Mn and optionally a machine X of FIG. 15.

In a still further embodiment, each machine M1, ..., Mn receives the unmodified asset (such as class or object) inclusive of one or more synchronization routines, but modifies the routines and then loads the asset (such as class or object) consisting of the

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now modified routines. Although one machine, such as the master or primary machine may customize or perform a different modification to the synchronization routine sent to each machine, this embodiment more readily enables the modification carried out by each

5   machine to be slightly different and to be enhanced, customized, and/or optimized based upon its particular machine architecture, hardware, processor, memory, configuration, operating system, or other factors, yet still similar, coherent and consistent with other machines with all other similar modifications and characteristics that may not need to be similar or identical.

10   In a further arrangement, a particular machine, say M1, loads the unmodified asset (such as class or object) inclusive of one or more synchronization routines and all other machines M2, M3, ..., Mn perform a modification to delete the synchronization routine(s) of the asset (such as class or object) and load the modified version.

15   In all of the described instances or embodiments, the supply or the communication of the asset code (such as class code or object code) to the machines M1, ..., Mn, and optionally inclusive of a machine X of FIG. 15, can be branched, distributed or communicated among and between the different machines in any combination or permutation; such as by providing direct machine to machine communication (for

20   example, M2 supplies each of M1, M3, M4, etc. directly), or by providing or using cascaded or sequential communication (for example, M2 supplies M1 which then supplies M3 which then supplies M4, and so on), or a combination of the direct and cascaded and/or sequential.

25   In a still further arrangement, the machines M1 to Mn, may send some or all load requests to an additional machine X (see for example the embodiment of FIG. 15), which performs the modification to the application code 50 inclusive of an (and possibly a plurality of) synchronization routine(s) via any of the afore mentioned methods, and returns the modified application code inclusive of the now modified synchronization

30   routine(s) to each of the machines M1 to Mn, and these machines in turn load the modified application code inclusive of the modified routines locally. In this arrangement, machines M1 to Mn forward all load requests to machine X, which returns a modified application program code 50 inclusive of modified synchronization routine(s) to each machine.   The modifications performed by machine X can include any of the

35   modifications covered under the scope of the present invention. This arrangement may of course be applied to some of the machines and other arrangements described herein before applied to other of the machines.

40   Persons skilled in the computing arts will be aware of various possible techniques that may be used in the modification of computer code, including but not limited to instrumentation, program transformation, translation, or compilation means.

One such technique is to make the modification(s) to the application code, without a preceding or consequential change of the language of the application code. Another

45   such technique is to convert the original code (for example, JAVA language source-code) into an intermediate representation (or intermediate-code language, or pseudo code), such as JAVA byte code. Once this conversion takes place the modification is made to the

byte code and then the conversion may be reversed. This gives the desired result of modified JAVA code.

5   A further possible technique is to convert the application program to machine code, either directly from source-code or via the abovementioned intermediate language or through some other intermediate means. Then the machine code is modified before being loaded and executed. A still further such technique is to convert the original code to an intermediate representation, which is thus modified and subsequently converted into machine code.

10   The present invention encompasses all such modification routes and also a combination of two, three or even more, of such routes.

EMBODIMENT INCLUDING MEMORY MANAGEMENT AND REPLICATION
15   ## OBJECT INITIALIZATION, FINALIZATION, AND SYNCHRONIZATION
Having now described structures, procedures, computer program code and tools, and other aspects and features of a multiple computer system and computing method utilizing at least one of memory management and replication object initialization, finalization, and synchronization it may readily be appreciated that these may also
20   optionally but advantageously be applied in any combination.
It may also be appreciated that the memory management, initialization, finalization, and/or synchronization aspects of the invention may be implemented or applied serially or sequentially or in parallel. For example, where the code is being scrutinized or analysed to identify or detect particular code sections relevant to
25   initialization, that same analysis or scrutinization may also attempt to identify or detect code sections relevant to finalization (or synchronization for example). Alternatively, separate sequential (or possibly overlapping) analysis and scrutiny may be utilized to separately detect code relevant to initialization and finalization and synchronization. Any required modification to the code may also be performed in combination or
30   separately, and furthermore, portions may be performed together while other portions are performed separately.

Having now described aspects of the memory management and replication, initialization, finalization, and synchronization, attention is now directed to an exemplary
35   operational scenario illustrating the manner in which application programs on two computers may simultaneously execute the same application program in a consistent, coherent manner.

In this regard, attention is directed to FIGS. 31-33, two laptop computers 101 and
40   102 are illustrated. The computers 101 and 102 are not necessarily identical and indeed, one can be an IBM or IBM-clone and the other can be an APPLE computer. The computers 101 and 102 have two screens 105, 115 two keyboards 106, 116 but a single mouse 107. The two machines 101, 102 are interconnected by a means of a single coaxial cable or twisted pair cable 314.
45
Two simple application programs are downloaded onto each of the machines 101, 102, the programs being modified as they are being loaded as described above. In this embodiment the first application is a simple calculator program and results in the image

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of a calculator 108 being displayed on the screen 105. The second program is a graphics program which displays four coloured blocks 109 which are of different colours and which move about at random within a rectangular box 310. Again, after loading, the box
5   310 is displayed on the screen 105. Each application operates independently so that the blocks 109 are in random motion on the screen 105 whilst numerals within the calculator 108 can be selected (with the mouse 107) together with a mathematical operator (such as addition or multiplication) so that the calculator 108 displays the result.

10   The mouse 107 can be used to "grab" the box 310 and move same to the right across the screen 105 and onto the screen 115 so as to arrive at the situation illustrated in FIG. 32. In this arrangement, the calculator application is being conducted on machine 101 whilst the graphics application resulting in display of box 310 is being conducted on machine 102.

15   However, as illustrated in FIG. 33, it is possible by means of the mouse 107 to drag the calculator 108 to the right as seen in FIG. 32 so as to have a part of the calculator 108 displayed by each of the screens 105, 115. Similarly, the box 310 can be dragged by means of the mouse 107 to the left as seen in FIG. 32 so that the box 310 is partially displayed by each of the screens 105, 115 as indicated FIG. 33. In this configuration, part
20   of the calculator operation is being performed on machine 101 and part on machine 102 whilst part of the graphics application is being carried out the machine 101 and the remainder is carried out on machine 102.

25   The foregoing describes only some embodiments of the present invention and modifications, obvious to those skilled in the art, can be made thereto without departing from the scope of the present invention. For example, reference to JAVA includes both the JAVA language and also JAVA platform and architecture.

30   In all described instances of modification, where the application code 50 is modified before, or during loading, or even after loading but before execution of the unmodified application code has commenced, it is to be understood that the modified application code is loaded in place of, and executed in place of, the unmodified application code subsequently to the modifications being performed.

35   Alternatively, in the instances where modification takes place after loading and after execution of the unmodified application code has commenced, it is to be understood that the unmodified application code may either be replaced with the modified application code in whole, corresponding to the modifications being performed, or alternatively, the unmodified application code may be replaced in part or incrementally as
40   the modifications are performed incrementally on the executing unmodified application code. Regardless of which such modification routes are used, the modifications subsequent to being performed execute in place of the unmodified application code.

     It is advantageous to use a global identifier is as a form of 'meta-name' or 'meta-
45   identity' for all the similar equivalent local objects (or classes, or assets or resources or the like) on each one of the plurality of machines M1, M2...Mn. For example, rather than having to keep track of each unique local name or identity of each similar equivalent local object on each machine of the plurality of similar equivalent objects, one may

instead define or use a global name corresponding to the plurality of similar equivalent objects on each machine (eg "globalname7787"), and with the understanding that each machine relates the global name to a specific local name or object (eg "globalname7787" corresponds to object "localobject456" on machine M1, and "globalname7787" corresponds to object "localobject885" on machine M2, and "globalname7787" corresponds to object "localobject111" on machine M3, and so forth).

It will also be apparent to those skilled in the art in light of the detailed description provided herein that in a table or list or other data structure created by each DRT 71 when initially recording or creating the list of all, or some subset of all objects (eg memory locations or fields), for each such recorded object on each machine M1, M2…Mn there is a name or identity which is common or similar on each of the machines M1, M2…Mn. However, in the individual machines the local object corresponding to a given name or identity will or may vary over time since each machine may, and generally will, store memory values or contents at different memory locations according to its own internal processes. Thus the table, or list, or other data structure in each of the DRTs will have, in general, different local memory locations corresponding to a single memory name or identity, but each global "memory name" or identity will have the same "memory value or content" stored in the different local memory locations. So for each global name there will be a family of corresponding independent local memory location with one family member in each of the computers. Although the local memory name may differ, the asset, object, location etc has essentially the same content or value. So the family is coherent.

It will also be apparent to those skilled in the art in light of the description provided herein that the abovementioned modification of the application program code 50 during loading can be accomplished in many ways or by a variety of means. These ways or means include, but are not limited to at least the following five ways and variations or combinations of these five, including by:

    (i)   re-compilation at loading,
    (ii)   a pre-compilation procedure prior to loading,
    (iii)   compilation prior to loading,
    (iv)   a "just-in-time" compilations, or
    (v)   re-compilation after loading (but, for example, before execution of the relevant or corresponding application code in a distributed environment).

Traditionally the term "compilation" implies a change in code or language, for example, from source to object code or one language to another. Clearly the use of the term "compilation" (and its grammatical equivalents) in the present specification is not so restricted and can also include or embrace modifications within the same code or language.

Given the fundamental concept of modifying memory manipulation operations to coordinate operation between and amongst a plurality of machines M1, M2…Mn, there are several different ways or embodiments in which this coordinated, coherent and consistent memory state and manipulation operation concept, method, and procedure may be carried out or implemented.

In the first embodiment, a particular machine, say machine M2, loads the asset (such as class or object) inclusive of memory manipulation operation(s), modifies it, and then loads each of the other machines M1, M3...Mn (either sequentially or simultaneously or according to any other order, routine or procedure) with the modified object (or class or other assert or resource) inclusive of the new modified memory manipulation operation. Note that there may be one or a plurality of memory manipulation operations corresponding to only one object in the application code, or there may be a plurality of memory manipulation operations corresponding to a plurality of objects in the application code. Note that in one embodiment, the memory manipulation operation(s) that is (are) loaded is executable intermediary code.

In this arrangement, which may be termed "master/slave" each of the slave (or secondary) machines M1, M3...Mn loads the modified object (or class), and inclusive of the new modified memory manipulation operation(s), that was sent to it over the computer communications network or other communications link or path be the master (or primary) machine, such as machine M2, or some other machine as a machine X. In a slight variation of this "master/slave" or "primary/secondary" arrangement, the computer communications network can be replaced by a shared storage device such as a shared file system, or a shared document/ file repository such as a shared database.

Note that the modification performed on each machine or computer need not and frequently will not be the same or identical. What is required is that they are modified in a similar enough way that each of the plurality of machines behaves consistently and coherently relative to the other machines. Furthermore, it will be appreciated that there are a myriad of ways to implement the modifications that may for example depend on the particular hardware, architecture, operating system, application program code, or the like or different factors. It will also be appreciated that implementation can be within an operating system, outside of or without the benefit of any operating system, inside the virtual machine, in an EPROM, in software in firmware, or in any combination of these,

In a still further embodiment, each machine M1, M2...Mn receives the unmodified asset (such as class or object) inclusive of one or more memory manipulation operation(s), but modifies the operations and then loads the asset (such as class or object) consisting of the now modified operations. Although one machine, such as the master or primary machine may customize or perform a different modification to the memory manipulation operation(s) sent to each machine, this embodiment more readily enables the modification carried out by each machine to be slightly different. It can thereby be enhanced, customized, and/or optimized based upon its particular machine architecture, hardware processor, memory, configuration, operating system, or other factors yet still be similar, coherent and consistent with the other machines and with all other similar modifications.

In all of the described instances or embodiments, the supply or the communication of the asset code (such as class code or object code) to the machines M1, M2...Mn and optionally inclusive of a machine X, can be branched, distributed or communication among and between the different machines in any combination or permutation; such as by providing direct machine to machine communication (for example, M2 supplies each of M1, M3, M4 etc. directly), or by providing or using cascaded or sequential

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communication (for example, M2 supplies M1 which then supplies M3 which then supplies M4, and so on) or a combination of the direct and cascaded and/or sequential.

The abovedescribed arrangement needs to be varied in the situation where the modification relates to a cleanup routine, finalization or similar, which is only to be carried out by one of the plurality of computers In this variation of this "master/slave" or "primary/secondary" arrangement, machine M2 loads the asset (such as class or object) inclusive of a cleanup routine in unmodified form on machine M2, and then (for example, M2 or each local machine) deletes the unmodified cleanup routine that had been present on the machine in whole or part from the asset (such as class or object) and loads by means of a computer communications network the modified code for the asset with the now modified or deleted cleanup routine on the other machines. Thus in this instance the modification is not a transformation, instrumentation, translation or compilation of the asset cleanup routine but a deletion of the cleanup routine on all machines except one. In one embodiment, the actual code-block of the finalization or cleanup routine is deleted on all machines except one, and this last machine therefore is the only machine that can execute the finalization routine because all other machines have deleted the finalization routine. One benefit of this approach is that no conflict arises between multiple machines executing the same finalization routine because only one machine has the routine.

The process of deleting the cleanup routine in its entirety can either be performed by the "master" machine (such as machine M2 or some other machine such as machine X) or alternatively by each other machine M1, M3...Mn upon receipt of the unmodified asset. An additional variation of this "master/slave" or "primary/secondary" arrangement is to use a shared storage device such as a shared file system, or a shared document/file repository such as a shared database as means of exchanging the code for the asset, class or object between machines M1, M2...Mn and optionally the server machine X.

In a further arrangement, a particular machine, say M1, loads the unmodified asset (such as class or object) inclusive of a finalization or cleanup routine and all the other machines M2, M3...Mn perform a modification to delete the cleanup routine of the asset (such as class or object) and load the modified version.

In a still further arrangement, the machines M1, M2...Mn, may send some or all load requests to the additional server machine X , which performs the modification to the application program code 50 (including or consisting of assets, and/or classes, and/or objects) and inclusive of finalization or cleanup routine(s), via any of the afore mentioned methods, and returns in the modified application program code inclusive of the now modified finalization or cleanup routine(s) to each of the machines M1 to Mn, and these machines in turn load the modified application program code inclusive of the modified routine(s) locally. In this arrangement, machines M1 to Mn forward all load requests to machine X, which returns a modified application program code inclusive of modified finalization or cleanup routine(s) to each machine. The modifications performed by machine X can include any of the modifications described. This arrangement may of course be applied to some only of the machines whilst other arrangements described herein are applied to others of the machines.

The abovementioned embodiment in which the code of the JAVA initialisation routine is modified, is based upon the assumption that either the run time system (say, JAVA HOTSPOT VIRTUAL MACHINE written in C and JAVA) or the operating system (LINUX written in C and Assembler, for example) of each machine M1...Mn will call the JAVA initialisation routine. It is possible to leave the JAVA initialisation routine unamended and instead amend the LINUX or HOTSPOT routine which calls the JAVA initialisation routine, so that if the object or class is already loaded, then the JAVA initialisation routine is not called. In order to embrace such an arrangement the term "initialisation routine" is to be understood to include within its scope both the JAVA initialisation routine and the "combination" of the JAVA initialisation routine <u>and</u> the LINUX or HOTSPOT code fragments which call or initiates the JAVA initialisation routine.

The abovementioned embodiment in which the code of the JAVA finalisation or clean up routine is modified, is based upon the assumption that either the run time system (say, JAVA HOTSPOT VIRTUAL MACHINE written in C and JAVA) or the operating system (LINUX written in C and Assembler, for example) of each machine M1...Mn will call the JAVA finalisation routine. It is possible to leave the JAVA finalisation routine unamended and instead amend the LINUX or HOTSPOT routine which calls the JAVA finalisation routine, so that if the object or class is not to be deleted, then the JAVA finalisation routine is not called. In order to embrace such an arrangement the term "finalisation routine" is to be understood to include within its scope both the JAVA finalisation routine and the "combination" of the JAVA finalisation routine <u>and</u> the LINUX or HOTSPOT code fragments which call or initiate the JAVA finalisation routine.

The abovementioned embodiment in which the code of the JAVA synchronization routine is modified, is based upon the assumption that either the run time system (say, JAVA HOTSPOT VIRTUAL MACHINE written in C and JAVA) or the operating system (LINUX written in C and Assembler, for example) of each machine M1...Mn will normally acquire the lock on the local machine (say M2) but not on any other machines (M1, M3 ...Mn). It is possible to leave the JAVA synchronization routine unamended and instead amend the LINUX or HOTSPOT routine which acquires the lock locally, so that it correspondingly acquires the lock on all other machines as well. In order to embrace such an arrangement the term "synchronization routine" is to be understood to include within its scope both the JAVA synchronization routine and the "combination" of the JAVA synchronization routine <u>and</u> the LINUX or HOTSPOT code fragments which perform lock acquisition and release.

The terms object and class used herein are derived from the JAVA environment and are intended to embrace similar terms derived from different environments such as dynamically linked libraries (DLL), or object code packages, or function unit or memory locations.

Those skilled in the programming arts will be aware that when additional code or instructions is/are inserted into an existing code or instruction set to modify same, the existing code or instruction set may well require further modification (such as for

example, by re-numbering of sequential instructions) so that offsets, branching, attributes, mark up and the like are catered for.

5   Similarly, in the JAVA language memory locations include, for example, both fields and array types. The above description deals with fields and the changes required for array types are essentially the same mutatis mutandis. Also the present invention is equally applicable to similar programming languages (including procedural, declarative and object orientated) to JAVA including Microsoft.NET platform and architecture (Visual Basic, Visual C/C^{++}, and C#) FORTRAN, C/C^{++}, COBOL, BASIC etc.

10   The terms object and class used herein are derived from the JAVA environment and are intended to embrace similar terms derived from different environments such as dynamically linked libraries (DLL), or object code packages, or function unit or memory locations.

15   Various means are described relative to embodiments of the invention, including for example but not limited to lock means, distributed run time means, modifier or modifying means, and the like. In at least one embodiment of the invention, any one or each of these various means may be implemented by computer program code statements
20   or instructions (possibly including by a plurality of computer program code statements or instructions) that execute within computer logic circuits, processors, ASICs, microprocessors, microcontrollers or other logic to modify the operation of such logic or circuits to accomplish the recited operation or function. In another embodiment, any one or each of these various means may be implemented in firmware and in other
25   embodiments such may be implemented in hardware. Furthermore, in at least one embodiment of the invention, any one or each of these various means may be implemented by a combination of computer program software, firmware, and/or hardware.

30   Any and each of the afore described methods, procedures, and/or routines may advantageously be implemented as a computer program and/or computer program product stored on any tangible media or existing in electronic, signal, or digital form. Such computer program or computer program products comprising instructions separately and/or organized as modules, programs, subroutines, or in any other way for
35   execution in processing logic such as in a processor or microprocessor of a computer, computing machine, or information appliance; the computer program or computer program products modifying the operation of the computer in which it executes or on a computer coupled with, connected to, or otherwise in signal communications with the computer on which the computer program or computer program product is present or
40   executing. Such a computer program or computer program product modifies the operation and architectural structure of the computer, computing machine, and/or information appliance to alter the technical operation of the computer and realize the technical effects described herein.

45   The invention may therefore includes a computer program product comprising a set of program instructions stored in a storage medium or existing electronically in any form and operable to permit a plurality of computers to carry out any of the methods, procedures, routines, or the like as described herein including in any of the claims.

Furthermore, the invention includes a plurality of computers interconnected via a communication network or other communications link or path and each operable to substantially simultaneously or concurrently execute the same or a different portion of an application code written to operate on only a single computer on a corresponding different one of computers. The computers are programmed to carry out any of the methods, procedures. or routines described in the specification or set forth in any of the claims, on being loaded with a computer program product. Similarly, the invention also includes within its scope a single computer arrayed to co-operate with like, or substantially similar, computers to form a multiple computer system.

The term "compromising" (and its grammatical variations) as used herein is used in the inclusive sense of "having" or "including" and not in the exclusive sense of "consisting only of".

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Annexure A

The following are program listings in the JAVA language:

A1.   This first excerpt is part of the modification code. It searches through the code array, and when it finds a putstatic instruction (opcode 178), it implements the
5   modifications.

```
// START
byte[] code =  Code_attribute.code;      // Bytecode of a given method in a
                                         // given classfile.

int code_length = Code_attribute.code_length;

int DRT = 99;         // Location of the CONSTANT_Methodref_info for the
                      // DRT.alert() method.

for (int i=0; i<code_length; i++){

    if ((code[i] & 0xff) == 179){ // Putstatic instruction.

        System.arraycopy(code, i+3, code, i+6, code_length-(i+3));

        code[i+3] = (byte) 184;     // Invokestatic instruction for the
                                    // DRT.alert() method.

        code[i+4] = (byte) ((DRT >>> 8) & 0xff);

        code[i+5] = (byte) (DRT & 0xff);

    }

)
// END
```

A2.   This second excerpt is part of the DRT.alert() method. This is the body of the DRT.alert() method when it is called.

```
// START
public static void alert(){

    synchronized (ALERT_LOCK){

        ALERT_LOCK.notify(); // Alerts a waiting DRT thread in the background.

    }

}
// END
```

A3.   This third excerpt is part of the DRT Sending. This code fragment shows the DRT in a separate thread, after being notified, sending the value across the network.

```
// START
MulticastSocket ms = DRT.getMulticastSocket();     // The multicast socket
                                                   // used by the DRT for
                                                   // communication.

byte nameTag = 33;          // This is the "name tag" on the network for this
                            // field.

Field field = modifiedClass.getDeclaredField("myField1");   // Stores
                                                            // the field
                                                            // from the
```

```
                                                     // modified
                                                     // class.

       // In this example, the field is a byte field.
 5     while (DRT.isRunning()){

           synchronized (ALERT_LOCK){

               ALERT_LOCK.wait();   // The DRT thread is waiting for the alert
10                                  // method to be called.

               byte[] b = new byte[]{nameTag, field.getByte(null)};  // Stores
                                                                      // the
                                                                      // nameTag
15                                                                    // and the
                                                                      // value
                                                                      // of the
                                                                      // field from
                                                                      // the modified
20                                                                    // class in a
                                                                      // buffer.

               DatagramPacket dp = new DatagramPacket(b, 0, b.length);

25             ms.send(dp);  // Send the buffer out across the network.

           }


       )
30 ·   // END
```

A4.   The fourth excerpt is part of the DRT receiving. This is a fragment of code to
receive a DRT sent alert over the network.

```
       // START
35     MulticastSocket ms = DRT.getMulticastSocket(); // The multicast socket
                                                       // used by the DRT for
                                                       // communication.

       DatagramPacket dp = new DatagramPacket(new byte[2], 0, 2);
40
       byte nameTag = 33;            // This is the "name tag" on the network for this
                                     // field.

       Field field = modifiedClass.getDeclaredField("myField1");  // Stores the
45                                                                 // field from
                                                                   // the modified
                                                                   // class.


       // In this example, the field is a byte field.
50     while (DRT.isRunning(){

           ms.receive(dp);  // Receive the previously sent buffer from the network.

           byte[] b = dp.getData();
55
           if (b[0] == nameTag){    // Check the nametags match.
               field.setByte(null, b[1]); // Write the value from the network packet
                                          // into the field location in memory.

60         }

       )
       // END
```

A5.   The fifth excerpt is an example application before modification has occurred.
Method void setValues(int, int)
```
    0 iload_1
    1 putstatic #3 <Field int staticValue>
    4 aload_0
    5 iload_2
    6 putfield #2 <Field int instanceValue>
    9 return
```

A6.   The sixth excerpt is the same example application in 5 after modification has been
performed. The modifications are highlighted in **bold**.
Method void setValues(int, int)
```
    0 iload_1
    1 putstatic #3 <Field int staticValue>
    4 ldc #4 <String "example">
    6 iconst_0
    7 invokestatic #5 <Method void alert(java.lang.Object, int)>
    10 aload_0
    11 iload_2
    12 putfield #2 <Field int instanceValue>
    15 aload_0
    16 iconst_1
    17 invokestatic #5 <Method void alert(java.lang.Object, int)>
    20 return
```

A7.   The seventh excerpt is the source-code of the example application used in excerpt
5 and 6.

```
import java.lang.*;

public class example{

   /** Shared static field. */
   public static int staticValue = 0;

   /** Shared instance field. */
   public int instanceValue = 0;

   /** Example method that writes to memory (instance field). */
   public void setValues(int a, int b){

       staticValue = a;

       instanceValue = b;

   }

}
```

A8.   The eighth excerpt is the source-code of FieldAlert, which alerts the "distributed run-time" to propagate a changed value.

```
   import java.lang.*;
   import java.util.*;
5  import java.net.*;
   import java.io.*;
   public class FieldAlert{

      /** Table of alerts. */
10    public final static Hashtable alerts = new Hashtable();

      /** Object handle. */
      public Object reference = null;

15
      /** Table of field alerts for this object. */
      public boolean[] fieldAlerts = null;

      /** Constructor. */
20    public FieldAlert(Object o, int initialFieldCount){
         reference = o;
         fieldAlerts = new boolean[initialFieldCount];
      }

25    /** Called when an application modifies a value. (Both objects and
         classes) */
      public static void alert(Object o, int fieldID){

         // Lock the alerts table.
30       synchronized (alerts){

            FieldAlert alert = (FieldAlert) alerts.get(o);

            if (alert == null){      // This object hasn't been alerted already,
35                                    // so add to alerts table.
               alert = new FieldAlert(o, fieldID + 1);
               alerts.put(o, alert);
            }

40          if (fieldID >= alert.fieldAlerts.length){
               // Ok, enlarge fieldAlerts array.
               boolean[] b = new boolean[fieldID+1];
               System.arraycopy(alert.fieldAlerts, 0, b, 0,
                  alert.fieldAlerts.length);
45             alert.fieldAlerts = b;
            }

            // Record the alert.
            alert.fieldAlerts[fieldID] = true;
50
            // Mark as pending.
            FieldSend.pending = true;      // Signal that there is one or more
                                           // propagations waiting.

55          // Finally, notify the waiting FieldSend thread(s)
            if (FieldSend.waiting){
               FieldSend.waiting = false;
               alerts.notify();
            }
60
         }

      }
```

)

5   A9.   The ninth excerpt is the source-code of FieldSend, which propagates changes
    values alerted to it via FieldAlert.

```
import java.lang.*;
import java.lang.reflect.*;
import java.util.*;
10  import java.net.*;
import java.io.*;

public class FieldSend implements Runnable(

15      /** Protocol specific values. */
        public final static int CLOSE = -1;
        public final static int NACK = 0;
        public final static int ACK = 1;
        public final static int PROPAGATE_OBJECT = 10;
20      public final static int PROPAGATE_CLASS = 20;

        /** FieldAlert network values. */
        public final static String group =
            System.getProperty("FieldAlert_network_group");
25      public final static int port =
            Integer.parseInt(System.getProperty("FieldAlert_network_port"));

        /** Table of global ID's for local objects. (hashcode-to-globalID
            mappings) */
30      public final static Hashtable objectToGlobalID = new Hashtable();

        /** Table of global ID's for local classnames. (classname-to-globalID
            mappings) */
        public final static Hashtable classNameToGlobalID = new Hashtable();
35
        /** Pending. True if a propagation is pending. */
        public static boolean pending = false;

        /** Waiting. True if the FieldSend thread(s) are waiting. */
40      public static boolean waiting = false;

        /** Background send thread. Propagates values as this thread is alerted
            to their alteration. */
        public void run(){
45
            System.out.println("FieldAlert_network_group=" + group);
            System.out.println("FieldAlert_network_port=" + port);

            try{
50
                // Create a DatagramSocket to send propagated field values.
                DatagramSocket datagramSocket =
                    new DatagramSocket(port, InetAddress.getByName(group));

55              // Next, create the buffer and packet for all transmissions.
                byte[] buffer = new byte[512];          // Working limit of 512 bytes
                                                        // per packet.
                DatagramPacket datagramPacket =
                    new DatagramPacket(buffer, 0, buffer.length);
60
                while (!Thread.interrupted()){

                    Object[] entries = null;
```

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```
            // Lock the alerts table.
            synchronized (FieldAlert.alerts){

5               // Await for an alert to propagate something.
                while (!pending){
                   waiting = true;
                   FieldAlert.alerts.wait();
                   waiting = false;
10              }

                pending = false;

                entries = FieldAlert.alerts.entrySet().toArray();
15
                // Clear alerts once we have copied them.
                FieldAlert.alerts.clear();

            }
20
            // Process each object alert in turn.
            for (int i=0; i<entries.length; i++){

                FieldAlert alert = (FieldAlert) entries[i];
25
                int index = 0;
                datagramPacket.setLength(buffer.length);

                Object reference = null;
30              if (alert.reference instanceof String){
                   // PROPAGATE_CLASS field operation.

                   buffer[index++] = (byte) ((PROPAGATE_CLASS >> 24) & 0xff);
                   buffer[index++] = (byte) ((PROPAGATE_CLASS >> 16) & 0xff);
35                 buffer[index++] = (byte) ((PROPAGATE_CLASS >> 8) & 0xff);
                   buffer[index++] = (byte) ((PROPAGATE_CLASS >> 0) & 0xff);

                   String name = (String) alert.reference;
                   int length = name.length();
40                 buffer[index++] = (byte) ((length >> 24) & 0xff);
                   buffer[index++] = (byte) ((length >> 16) & 0xff);
                   buffer[index++] = (byte) ((length >> 8) & 0xff);
                   buffer[index++] = (byte) ((length >> 0) & 0xff);

45                 byte[] bytes = name.getBytes();
                   System.arraycopy(bytes, 0, buffer, index, length);
                   index += length;

                )else{                              // PROPAGATE_OBJECT field operation.
50
                   buffer[index++] =
                       (byte) ((PROPAGATE_OBJECT >> 24) & 0xff);
                   buffer[index++] =
                       (byte) ((PROPAGATE_OBJECT >> 16) & 0xff);
55                 buffer[index++] = (byte) ((PROPAGATE_OBJECT >> 8) & 0xff);
                   buffer[index++] = (byte) ((PROPAGATE_OBJECT >> 0) & 0xff);

                   int globalID = ((Integer)
                       objectToGlobalID.get(alert.reference)).intValue();
60
                   buffer[index++] = (byte) ((globalID >> 24) & 0xff);
                   buffer[index++] = (byte) ((globalID >> 16) & 0xff);
                   buffer[index++] = (byte) ((globalID >> 8) & 0xff);
                   buffer[index++] = (byte) ((globalID >> 0) & 0xff);
65
```

```
                   reference = alert.reference;

               )

5              // Use reflection to get a table of fields that correspond to
               // the field indexes used internally.
               Field[] fields = null;
               if (reference == null){
10                 fields = FieldLoader.loadClass((String)
                       alert.reference).getDeclaredFields();
               )else(
                   fields = alert.reference.getClass().getDeclaredFields();
               ]

15             // Now encode in batch mode the fieldID/value pairs.
               for (int j=0; j<alert.fieldAlerts.length; j++){

                   if (alert.fieldAlerts[j] == false)
                       continue;
20
                   buffer[index++] = (byte) ((j >> 24) & 0xff);
                   buffer[index++] = (byte) ((j >> 16) & 0xff);
                   buffer[index++] = (byte) ((j >> 8) & 0xff);
                   buffer[index++] = (byte) ((j >> 0) & 0xff);
25
                   // Encode value.
                   Class type = fields[j].getType();
                   if (type == Boolean.TYPE){
                       buffer[index++] =(byte)
30                         (fields[j].getBoolean(reference)? 1 : 0);
                   )else if (type == Byte.TYPE){
                       buffer[index++] = fields[j].getByte(reference);
                   )else if (type == Short.TYPE){
                       short v = fields[j].getShort(reference);
35                     buffer[index++] = (byte) ((v >> 8) & 0xff);
                       buffer[index++] = (byte) ((v >> 0) & 0xff);
                   )else if (type == Character.TYPE){
                       char v = fields[j].getChar(reference);
                       buffer[index++] = (byte) ((v >> 8) & 0xff);
40                     buffer[index++] = (byte) ((v >> 0) & 0xff);
                   )else if (type == Integer.TYPE){
                       int v = fields[j].getInt(reference);
                       buffer[index++] = (byte) ((v >> 24) & 0xff);
                       buffer[index++] = (byte) ((v >> 16) & 0xff);
45                     buffer[index++] = (byte) ((v >> 8) & 0xff);
                       buffer[index++] = (byte) ((v >> 0) & 0xff);
                   )else if (type == Float.TYPE){
                       int v = Float.floatToIntBits(
                           fields[j].getFloat(reference));
50                     buffer[index++] = (byte) ((v >> 24) & 0xff);
                       buffer[index++] = (byte) ((v >> 16) & 0xff);
                       buffer[index++] = (byte) ((v >> 8) & 0xff);
                       buffer[index++] = (byte) ((v >> 0) & 0xff);
                   )else if (type == Long.TYPE){
55                     long v = fields[j].getLong(reference);
                       buffer[index++] = (byte) ((v >> 56) & 0xff);
                       buffer[index++] = (byte) ((v >> 48) & 0xff);
                       buffer[index++] = (byte) ((v >> 40) & 0xff);
                       buffer[index++] = (byte) ((v >> 32) & 0xff);
60                     buffer[index++] = (byte) ((v >> 24) & 0xff);
                       buffer[index++] = (byte) ((v >> 16) & 0xff);
                       buffer[index++] = (byte) ((v >> 8) & 0xff);
                       buffer[index++] = (byte) ((v >> 0) & 0xff);
                   )else if (type == Double.TYPE){
65                     long v = Double.doubleToLongBits(
```

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```
                    fields[j].getDouble(reference));
                buffer[index++] = (byte) ((v >> 56) & 0xff);
                buffer[index++] = (byte) ((v >> 48) & 0xff);
                buffer[index++] = (byte) ((v >> 40) & 0xff);
5               buffer[index++] = (byte) ((v >> 32) & 0xff);
                buffer[index++] = (byte) ((v >> 24) & 0xff);
                buffer[index++] = (byte) ((v >> 16) & 0xff);
                buffer[index++] = (byte) ((v >> 8) & 0xff);
                buffer[index++] = (byte) ((v >> 0) & 0xff);
            }else{
10              throw new AssertionError("Unsupported type.");
            }


15          )

            // Now set the length of the datagrampacket.
            datagramPacket.setLength(index);

20          // Now send the packet.
            datagramSocket.send(datagramPacket);


        )

25      )

    }catch (Exception e){
        throw new AssertionError("Exception: " + e.toString());
    )
30
}


}
35
```

A10.   The tenth excerpt is the source-code of FieldReceive, which receives propagated
changed values sent via FieldSend.
```
import java.lang.*;
40  import java.lang.reflect.*;
    import java.util.*;
    import java.net.*;
    import java.io.*;

    public class FieldReceive implements Runnable{
45
        /** Protocol specific values. */
        public final static int CLOSE = -1;
        public final static int NACK = 0;
        public final static int ACK = 1;
50      public final static int PROPAGATE_OBJECT = 10;
        public final static int PROPAGATE_CLASS = 20;

        /** FieldAlert network values. */
        public final static String group =
55          System.getProperty("FieldAlert_network_group");
        public final static int port =
            Integer.parseInt(System.getProperty("FieldAlert_network_port"));

        /** Table of global ID's for local objects. (globalID-to-hashcode
60          mappings) */
        public final static Hashtable globalIDToObject = new Hashtable();

        /** Table of global ID's for local classnames. (globalID-to-classname
            mappings) */
```

```
     public final static Hashtable globalIDToClassName = new Hashtable();

     /** Called when an application is to acquire a lock. */
     public void run(){

         System.out.println("FieldAlert_network_group=" + group);
         System.out.println("FieldAlert_network_port=" + port);

         try{

             // Create a DatagramSocket to send propagated field values from
             MulticastSocket multicastSocket = new MulticastSocket(port);
             multicastSocket.joinGroup(InetAddress.getByName(group));

             // Next, create the buffer and packet for all transmissions.
             byte[] buffer = new byte[512];                // Working limit of 512
                                                           // bytes per packet.
             DatagramPacket datagramPacket =
                 new DatagramPacket(buffer, 0, buffer.length);

             while (!Thread.interrupted()){

                 // Make sure to reset length.
                 datagramPacket.setLength(buffer.length);

                 // Receive the next available packet.
                 multicastSocket.receive(datagramPacket);

                 int index = 0, length = datagramPacket.getLength();

                 // Decode the command.
                 int command = (int) (((buffer[index++] & 0xff) << 24)
                     | ((buffer[index++] & 0xff) << 16)
                     | ((buffer[index++] & 0xff) << 8)
                     | (buffer[index++] & 0xff));

                 if (command == PROPAGATE_OBJECT){   // Propagate operation for
                                                     // object fields.

                     // Decode global id.
                     int globalID = (int) (((buffer[index++] & 0xff) << 24)
                         | ((buffer[index++] & 0xff) << 16)
                         | ((buffer[index++] & 0xff) << 8)
                         | (buffer[index++] & 0xff));

                     // Now, need to resolve the object in question.
                     Object reference = globalIDToObject.get(
                         new Integer(globalID));

                     // Next, get the array of fields for this object.
                     Field[] fields = reference.getClass().getDeclaredFields();

                     while (index < length){

                         // Decode the field id.
                         int fieldID = (int) (((buffer[index++] & 0xff) << 24)
                             | ((buffer[index++] & 0xff) << 16)
                             | ((buffer[index++] & 0xff) << 8)
                             | (buffer[index++] & 0xff));

                         // Determine value length based on corresponding field
                         // type.
                         Field field = fields[fieldID];
                         Class type = field.getType();
                         if (type == Boolean.TYPE){
```

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```
                    boolean v = (buffer[index++] == 1 ? true : false);
                    field.setBoolean(reference, v);
                }else if (type == Byte.TYPE){
                    byte v = buffer[index++];
                    field.setByte(reference, v);
                }else if (type == Short.TYPE){
                    short v = (short) (((buffer[index++] & 0xff) << 8)
                        | (buffer[index++] & 0xff));
                    field.setShort(reference, v);
                }else if (type == Character.TYPE){
                    char v = (char) (((buffer[index++] & 0xff) << 8)
                        | (buffer[index++] & 0xff));
                    field.setChar(reference, v);
                }else if (type == Integer.TYPE){
                    int v = (int) (((buffer[index++] & 0xff) << 24)
                        | ((buffer[index++] & 0xff) << 16)
                        | ((buffer[index++] & 0xff) << 8)
                        | (buffer[index++] & 0xff));
                    field.setInt(reference, v);
                }else if (type == Float.TYPE){
                    int v = (int) (((buffer[index++] & 0xff) << 24)
                        | ((buffer[index++] & 0xff) << 16)
                        | ((buffer[index++] & 0xff) << 8)
                        | (buffer[index++] & 0xff));
                    field.setFloat(reference, Float.intBitsToFloat(v));
                }else if (type == Long.TYPE){
                    long v = (long) (((buffer[index++] & 0xff) << 56)
                        | ((buffer[index++] & 0xff) << 48)
                        | ((buffer[index++] & 0xff) << 40)
                        | ((buffer[index++] & 0xff) << 32)
                        | ((buffer[index++] & 0xff) << 24)
                        | ((buffer[index++] & 0xff) << 16)
                        | ((buffer[index++] & 0xff) << 8)
                        | (buffer[index++] & 0xff));
                    field.setLong(reference, v);
                }else if (type == Double.TYPE){
                    long v = (long) (((buffer[index++] & 0xff) << 56)
                        | ((buffer[index++] & 0xff) << 48)
                        | ((buffer[index++] & 0xff) << 40)
                        | ((buffer[index++] & 0xff) << 32)
                        | ((buffer[index++] & 0xff) << 24)
                        | ((buffer[index++] & 0xff) << 16)
                        | ((buffer[index++] & 0xff) << 8)
                        | (buffer[index++] & 0xff));
                    field.setDouble(reference, Double.longBitsToDouble(v));
                }else{
                    throw new AssertionError("Unsupported type.");
                }

            }

        }else if (command == PROPAGATE_CLASS){    // Propagate an update
                                                  // to class fields.

            // Decode the classname.
            int nameLength = (int) (((buffer[index++] & 0xff) << 24)
                | ((buffer[index++] & 0xff) << 16)
                | ((buffer[index++] & 0xff) << 8)
                | (buffer[index++] & 0xff));
            String name = new String(buffer, index, nameLength);
            index += nameLength;

            // Next, get the array of fields for this class.
            Field[] fields =
                FieldLoader.loadClass(name).getDeclaredFields();
```

```
                // Decode all batched fields included in this propagation
                // packet.
                while (index < length){

                    // Decode the field id.
                    int fieldID = (int) (((buffer[index++] & 0xff) << 24)
                        | ((buffer[index++] & 0xff) << 16)
                        | ((buffer[index++] & 0xff) << 8)
                        | (buffer[index++] & 0xff));

                    // Determine field type to determine value length.
                    Field field = fields[fieldID];
                    Class type = field.getType();
                    if (type == Boolean.TYPE){
                        boolean v = (buffer[index++] == 1 ? true : false);
                        field.setBoolean(null, v);
                    }else if (type == Byte.TYPE){
                        byte v = buffer[index++];
                        field.setByte(null, v);
                    }else if (type == Short.TYPE){
                        short v = (short) (((buffer[index++] & 0xff) << 8)
                            | (buffer[index++] & 0xff));
                        field.setShort(null, v);
                    }else if (type == Character.TYPE){
                        char v = (char) (((buffer[index++] & 0xff) << 8)
                            | (buffer[index++] & 0xff));
                        field.setChar(null, v);
                    }else if (type == Integer.TYPE){
                        int v = (int) (((buffer[index++] & 0xff) << 24)
                            | ((buffer[index++] & 0xff) << 16)
                            | ((buffer[index++] & 0xff) << 8)
                            | (buffer[index++] & 0xff));
                        field.setInt(null, v);
                    }else if (type == Float.TYPE){
                        int v = (int) (((buffer[index++] & 0xff) << 24)
                            | ((buffer[index++] & 0xff) << 16)
                            | ((buffer[index++] & 0xff) << 8)
                            | (buffer[index++] & 0xff));
                        field.setFloat(null, Float.intBitsToFloat(v));
                    }else if (type == Long.TYPE){
                        long v = (long) (((buffer[index++] & 0xff) << 56)
                            | ((buffer[index++] & 0xff) << 48)
                            | ((buffer[index++] & 0xff) << 40)
                            | ((buffer[index++] & 0xff) << 32)
                            | ((buffer[index++] & 0xff) << 24)
                            | ((buffer[index++] & 0xff) << 16)
                            | ((buffer[index++] & 0xff) << 8)
                            | (buffer[index++] & 0xff));
                        field.setLong(null, v);
                    }else if (type == Double.TYPE){
                        long v = (long) (((buffer[index++] & 0xff) << 56)
                            | ((buffer[index++] & 0xff) << 48)
                            | ((buffer[index++] & 0xff) << 40)
                            | ((buffer[index++] & 0xff) << 32)
                            | ((buffer[index++] & 0xff) << 24)
                            | ((buffer[index++] & 0xff) << 16)
                            | ((buffer[index++] & 0xff) << 8)
                            | (buffer[index++] & 0xff));
                        field.setDouble(null, Double.longBitsToDouble(v));
                    }else{          // Unsupported field type.
                        throw new AssertionError("Unsupported type.");
                    }

                }
```

```
               }

           }
5
       }catch (Exception e){
           throw new AssertionError("Exception: " + e.toString());
       }

10    }


    )
    A11. FieldLoader.java
15  This excerpt is the source-code of FieldLoader, which modifies an application as it is
    being loaded.
    import java.lang.*;
    import java.io.*;
    import java.net.*;
20
    public class FieldLoader extends URLClassLoader{

       public FieldLoader(URL[] urls){
           super(urls);
25     }

       protected Class findClass(String name)
       throws ClassNotFoundException{

30     ClassFile cf = null;

       try{

           BufferedInputStream in =
35             new BufferedInputStream(findResource(
               name.replace('.', '/').concat(".class")).openStream());

           cf = new ClassFile(in);

40     }catch (Exception e){throw new ClassNotFoundException(e.toString());}

       // Class-wide pointers to the ldc and alert index.
       int ldcindex = -1;
       int alertindex = -1;
45
       for (int i=0; i<cf.methods_count; i++){
          for (int j=0; j<cf.methods[i].attributes_count; j++){
             if (!(cf.methods[i].attributes[j] instanceof Code_attribute))
                continue;
50
             Code_attribute ca = (Code_attribute) cf.methods[i].attributes[j];

             boolean changed = false;

55           for (int z=0; z<ca.code.length; z++){
                if ((ca.code[z][0] & 0xff) == 179){    // Opcode for a PUTSTATIC
                                                       // instruction.
                   changed = true;

60                 // The code below only supports fields in this class.
                   // Thus, first off, check that this field is local to this
                   // class.
                   CONSTANT_Fieldref_info fi = (CONSTANT_Fieldref_info)
```

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```
        cf.constant_pool[(int) (((ca.code[z][1] & 0xff) << 8) |
        (ca.code[z][2] & 0xff))];
    CONSTANT_Class_info ci = (CONSTANT_Class_info)
        cf.constant_pool[fi.class_index];
    String className =
        cf.constant_pool[ci.name_index].toString();
    if (!name.equals(className)){
        throw new AssertionError("This code only supports fields "
            "local to this class");
    }


    // Ok, now search for the fields name and index.
    int index = 0;
    CONSTANT_NameAndType_info ni = (CONSTANT_NameAndType_info)
        cf.constant_pool[fi.name_and_type_index];
    String fieldName =
        cf.constant_pool[ni.name_index].toString();
    for (int a=0; a<cf.fields_count; a++){
        String fn = cf.constant_pool[
            cf.fields[a].name_index].toString();
        if (fieldName.equals(fn)){
            index = a;
            break;
        }
    }

    // Next, realign the code array, making room for the
    // insertions.
    byte[][] code2 = new byte[ca.code.length+3][];
    System.arraycopy(ca.code, 0, code2, 0, z+1);
    System.arraycopy(ca.code, z+1, code2, z+4,
        ca.code.length-(z+1));
    ca.code = code2;

    // Next, insert the LDC_W instruction.
    if (ldcindex == -1){
        CONSTANT_String_info csi =
            new CONSTANT_String_info(ci.name_index);
        cp_info[] cpi = new cp_info[cf.constant_pool.length+1];
        System.arraycopy(cf.constant_pool, 0, cpi, 0,
            cf.constant_pool.length);
        cpi[cpi.length - 1] = csi;
        ldcindex = cpi.length-1;
        cf.constant_pool = cpi;
        cf.constant_pool_count++;
    }
    ca.code[z+1] = new byte[3];
    ca.code[z+1][0] = (byte) 19;
    ca.code[z+1][1] = (byte) ((ldcindex >> 8) & 0xff);
    ca.code[z+1][2] = (byte) (ldcindex & 0xff);


    // Next, insert the SIPUSH instruction.
    ca.code[z+2] = new byte[3];
    ca.code[z+2][0] = (byte) 17;
    ca.code[z+2][1] = (byte) ((index >> 8) & 0xff);
    ca.code[z+2][2] = (byte) (index & 0xff);

    // Finally, insert the INVOKESTATIC instruction.
    if (alertindex == -1){
        // This is the first time this class is encourtering the
        // alert instruction, so have to add it to the constant
        // pool.
        cp_info[] cpi = new cp_info[cf.constant_pool.length+6];
```

```
                     System.arraycopy(cf.constant_pool, 0, cpi, 0,
                        cf.constant_pool.length);
                     cf.constant_pool = cpi;
                     cf.constant_pool_count += 6;

                     CONSTANT_Utf8_info u1 =
                        new CONSTANT_Utf8_info("FieldAlert");
                     cf.constant_pool[cf.constant_pool.length-6] = u1;

                     CONSTANT_Class_info c1 = new CONSTANT_Class_info(
                        cf.constant_pool_count-6);
                     cf.constant_pool[cf.constant_pool.length-5] = c1;

                     u1 = new CONSTANT_Utf8_info("alert");
                     cf.constant_pool[cf.constant_pool.length-4] = u1;

                     u1 = new CONSTANT_Utf8_info("(Ljava/lang/Object;I)V");
                     cf.constant_pool[cf.constant_pool.length-3] = u1;

                     CONSTANT_NameAndType_info n1 =
                        new CONSTANT_NameAndType_info(
                        cf.constant_pool.length-4, cf.constant_pool.length-3);
                     cf.constant_pool[cf.constant_pool.length-2] = n1;

                     CONSTANT_Methodref_info m1 = new CONSTANT_Methodref_info(
                        cf.constant_pool.length-5, cf.constant_pool.length-2);
                     cf.constant_pool[cf.constant_pool.length-1] = m1;
                     alertindex = cf.constant_pool.length-1;
                  )
                  ca.code[z+3] = new byte[3];
                  ca.code[z+3][0] = (byte) 184;
                  ca.code[z+3][1] = (byte) ((alertindex >> 8) & 0xff);
                  ca.code[z+3][2] = (byte) (alertindex & 0xff);

                  // And lastly, increase the CODE_LENGTH and ATTRIBUTE_LENGTH
                  // values.
                  ca.code_length += 9;
                  ca.attribute_length += 9;

               )

            )

         // If we changed this method, then increase the stack size by one.
         if (changed){
            ca.max_stack++;         // Just to make sure.
         )

      }
   )


   try{

      ByteArrayOutputStream out = new ByteArrayOutputStream();

      cf.serialize(out);

      byte[] b = out.toByteArray();

      return defineClass(name, b, 0, b.length);

   }catch (Exception e){
      throw new ClassNotFoundException(name);
   )
```

```
        )

    )
5
    A12. Attribute_info.java
    Convience class for representing attribute_info structures within ClassFiles.
    import java.lang.*;
    import java.io.*;
10
    /** This abstract class represents all types of attribute_info
     *  that are used in the JVM specifications.
     *
     *  All new attribute_info subclasses are to always inherit from this
15   *  class.
     */
    public abstract class attribute_info(

        public int attribute_name_index;
20      public int attribute_length;

        /** This is used by subclasses to register themselves
         *  to their parent classFile.
         */
25      attribute_info(ClassFile cf)()

        /** Used during input serialization by ClassFile only. */
        attribute_info(ClassFile cf, DataInputStream in)
            throws IOException(
30          attribute_name_index = in.readChar();
            attribute_length = in.readInt();
        )

        /** Used during output serialization by ClassFile only. */
35      void serialize(DataOutputStream out)
            throws IOException(
            cut.writeChar(attribute_name_index);
            out.writeInt(attribute_length);
        )
40
        /** This class represents an unknown attribute_info that
         *  this current version of classfile specification does
         *  not understand.
         */
45      public final static class Unknown extends attribute_info(

            byte[] info;

            /** Used during input serialization by ClassFile only. */
50          Unknown(ClassFile cf, DataInputStream in)
                throws IOException(
                super(cf, in);
                info = new byte[attribute_length];
                in.read(info, 0, attribute_length);
55          )

            /** Used during output serialization by ClassFile only. */
            void serialize(DataOutputStream out)
                throws IOException(
60              ByteArrayOutputStream baos = new ByteArrayOutputStream();

                super.serialize(out);
                out.write(info, 0, attribute_length);
            )
```

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```
        )

    )

5   A13. ClassFile.java
    Convience class for representing ClassFile structures.
    import java.lang.*;
    import java.io.*;
10  import java.util.*;

    /** The ClassFile follows verbatim from the JVM specification.  */
    public final class ClassFile {

15      public int magic;
        public int minor_version;
        public int major_version;
        public int constant_pool_count;
        public cp_info[] constant_pool;
20      public int access_flags;
        public int this_class;
        public int super_class;
        public int interfaces_count;
        public int[] interfaces;
25      public int fields_count;
        public field_info[] fields;
        public int methods_count;
        public method_info[] methods;
        public int attributes_count;
30      public attribute_info[] attributes;

        /** Constructor. Takes in a byte stream representation and transforms
         *  each of the attributes in the ClassFile into objects to allow for
         *  easier manipulation.
35       */
        public ClassFile(InputStream ins)
            throws IOException{
            DataInputStream in = (ins instanceof DataInputStream ?
                (DataInputStream) ins : new DataInputStream(ins));
40          magic = in.readInt();
            minor_version = in.readChar();
            major_version = in.readChar();
            constant_pool_count = in.readChar();
            constant_pool = new cp_info[constant_pool_count];
45          for (int i=1; i<constant_pool_count; i++){
                in.mark(1);
                int s = in.read();
                in.reset();
                switch (s){
50                  case 1:
                        constant_pool[i] = new CONSTANT_Utf8_info(this, in);
                        break;
                    case 3:
                        constant_pool[i] = new CONSTANT_Integer_info(this, in);
55                      break;
                    case 4:
                        constant_pool[i] = new CONSTANT_Float_info(this, in);
                        break;
                    case 5:
60                      constant_pool[i] = new CONSTANT_Long_info(this, in);
                        i++;
                        break;
                    case 6:
                        constant_pool[i] = new CONSTANT_Double_info(this, in);
```

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```
                    i++;
                    break;
                case 7:
                    constant_pool[i] = new CONSTANT_Class_info(this, in);
                    break;
                case 8:
                    constant_pool[i] = new CONSTANT_String_info(this, in);
                    break;
                case 9:
                    constant_pool[i] = new CONSTANT_Fieldref_info(this, in);
                    break;
                case 10:
                    constant_pool[i] = new CONSTANT_Methodref_info(this, in);
                    break;
                case 11:
                    constant_pool[i] =
                        new CONSTANT_InterfaceMethodref_info(this, in);
                    break;
                case 12:
                    constant_pool[i] = new CONSTANT_NameAndType_info(this, in);
                    break;
                default:
                    throw new ClassFormatError("Invalid ConstantPoolTag");
            }
        )
        access_flags = in.readChar();
        this_class = in.readChar();
        super_class = in.readChar();
        interfaces_count = in.readChar();
        interfaces = new int[interfaces_count];
        for (int i=0; i<interfaces_count; i++)
            interfaces[i] = in.readChar();
        fields_count = in.readChar();
        fields = new field_info[fields_count];
        for (int i=0; i<fields_count; i++) {
            fields[i] = new field_info(this, in);
        )
        methods_count = in.readChar();
        methods = new method_info[methods_count];
        for (int i=0; i<methods_count; i++) {
            methods[i] = new method_info(this, in);
        )
        attributes_count = in.readChar();
        attributes = new attribute_info[attributes_count];
        for (int i=0; i<attributes_count; i++) {
            in.mark(2);
            String s = constant_pool[in.readChar()].toString();
            in.reset();
            if (s.equals("SourceFile"))
                attributes[i] = new SourceFile_attribute(this, in);
            else if (s.equals("Deprecated"))
                attributes[i] = new Deprecated_attribute(this, in);
            else if (s.equals("InnerClasses"))
                attributes[i] = new InnerClasses_attribute(this, in);
            else
                attributes[i] = new attribute_info.Unknown(this, in);
        )
    )

    /** Serializes the ClassFile object into a byte stream. */
    public void serialize(OutputStream o)
        throws IOException(
        DataOutputStream out = (o instanceof DataOutputStream ?
            (DataOutputStream) o : new DataOutputStream(o));
        out.writeInt(magic);
```

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```
          out.writeChar(minor_version);
          out.writeChar(major_version);
          out.writeChar(constant_pool_count);
          for (int i=1; i<constant_pool_count; i++){
5             constant_pool[i].serialize(out);
              if (constant_pool[i] instanceof CONSTANT_Long_info ||
                      constant_pool[i] instanceof CONSTANT_Double_info)
                  i++;
          }
10        out.writeChar(access_flags);
          out.writeChar(this_class);
          out.writeChar(super_class);
          out.writeChar(interfaces_count);
          for (int i=0; i<interfaces_count; i++)
15            out.writeChar(interfaces[i]);
          out.writeChar(fields_count);
          for (int i=0; i<fields_count; i++)
              fields[i].serialize(out);
          out.writeChar(methods_count);
20        for (int i=0; i<methods_count; i++)
              methods[i].serialize(out);
          out.writeChar(attributes_count);
          for (int i=0; i<attributes_count; i++)
              attributes[i].serialize(out);
25        // Flush the outputstream just to make sure.
          out.flush();
      }

30 }

A14. Code_attribute.java
Convience class for representing Code_attribute structures within ClassFiles.
import java.util.*;
import java.lang.*;
35 import java.io.*;

/**
 *  The code[] is stored as a 2D array.  */
public final class Code_attribute extends attribute_info{
40
      public int max_stack;
      public int max_locals;
      public int code_length;
      public byte[][] code;
45    public int exception_table_length;
      public exception_table[] exception_table;
      public int attributes_count;
      public attribute_info[] attributes;

50    /** Internal class that handles the exception table. */
      public final static class exception_table{
          public int start_pc;
          public int end_pc;
          public int handler_pc;
55        public int catch_type;
      }

      /** Constructor called only by method_info. */
      Code_attribute(ClassFile cf, int ani, int al, int ms, int ml, int cl,
60                byte[][] cd, int etl, exception_table[] et, int ac,
                      attribute_info[] a){
          super(cf);
          attribute_name_index = ani;
          attribute_length = al;
```

```
            max_stack = ms;
            max_locals = ml;
            code_length = cl;
            code = cd;
5           exception_table_length = etl;
            exception_table = et;
            attributes_count = ac;
            attributes = a;
        )
10
        /** Used during input serialization by ClassFile only. */
        Code_attribute(ClassFile cf, DataInputStream in)
            throws IOException(
            super(cf, in);
15          max_stack = in.readChar();
            max_locals = in.readChar();
            code_length = in.readInt();
            code = new byte[code_length][];

20          int i = 0;
            for (int pos=0; pos<code_length; i++){
                in.mark(1);
                int s = in.read();
                in.reset();
25              switch (s){
                    case 16:
                    case 18:
                    case 21:
                    case 22:
30                  case 23:
                    case 24:
                    case 25:
                    case 54:
                    case 55:
35                  case 56:
                    case 57:
                    case 58:
                    case 169:
                    case 188:
40                  case 196:
                        code[i] = new byte[2];
                        break;
                    case 17:
                    case 19:
45                  case 20:
                    case 132:
                    case 153:
                    case 154:
                    case 155:
50                  case 156:
                    case 157:
                    case 158:
                    case 159:
                    case 160:
55                  case 161:
                    case 162:
                    case 163:
                    case 164:
                    case 165:
60                  case 166:
                    case 167:
                    case 168:
                    case 178:
                    case 179:
65                  case 180:
```

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```
                case 181:
                case 182:
                case 183:
                case 184:
                case 187:
                case 189:
                case 192:
                case 193:
                case 198:
                case 199:
                case 209:
                    code[i] = new byte[3];
                    break;
                case 197:
                    code[i] = new byte[4];
                    break;
                case 185:
                case 200:
                case 201:
                    code[i] = new byte[5];
                    break;
                case 170:{
                    int pad = 3 - (pos % 4);
                    in.mark(pad+13);                            // highbyte
                    in.skipBytes(pad+5);                        // lowbyte
                    int low = in.readInt();
                    code[i] =
                        new byte[pad + 13 + ((in.readInt() - low + 1) * 4)];
                    in.reset();
                    break;
                }case 171:{
                    int pad = 3 - (pos % 4);
                    in.mark(pad+9);
                    in.skipBytes(pad+5);
                    code[i] = new byte[pad + 9 + (in.readInt() * 8)];
                    in.reset();
                    break;
                }default:
                    code[i] = new byte[1];
            }
            in.read(code[i], 0, code[i].length);
            pos += code[i].length;
        )

        // adjust the array to the new size and store the size
        byte[][] temp = new byte[i][];
        System.arraycopy(code, 0, temp, 0, i);
        code = temp;

        exception_table_length = in.readChar();
        exception_table =
            new Code_attribute.exception_table[exception_table_length];
        for (i=0; i<exception_table_length; i++){
            exception_table[i] = new exception_table();
            exception_table[i].start_pc = in.readChar();
            exception_table[i].end_pc = in.readChar();
            exception_table[i].handler_pc = in.readChar();
            exception_table[i].catch_type = in.readChar();
        )
        attributes_count = in.readChar();
        attributes = new attribute_info[attributes_count];
        for (i=0; i<attributes_count; i++){
            in.mark(2);
            String s = cf.constant_pool[in.readChar()].toString();
            in.reset();
```

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```
            if (s.equals("LineNumberTable"))
                attributes[i] = new LineNumberTable_attribute(cf, in);
            else if (s.equals("LocalVariableTable"))
                attributes[i] = new LocalVariableTable_attribute(cf, in);
            else
                attributes[i] = new attribute_info.Unknown(cf, in);
        )
    }

    /** Used during output serialization by ClassFile only.
     */
    void serialize(DataOutputStream out)
        throws IOException{
            attribute_length = 12 + code_length +
                (exception_table_length * 8);
            for (int i=0; i<attributes_count; i++)
                attribute_length += attributes[i].attribute_length + 6;
            super.serialize(out);
            out.writeChar(max_stack);
            out.writeChar(max_locals);
            out.writeInt(code_length);
            for (int i=0, pos=0; pos<code_length; i++){
                out.write(code[i], 0, code[i].length);
                pos += code[i].length;
            )
            out.writeChar(exception_table_length);
            for (int i=0; i<exception_table_length; i++){
                out.writeChar(exception_table[i].start_pc);
                out.writeChar(exception_table[i].end_pc);
                out.writeChar(exception_table[i].handler_pc);
                out.writeChar(exception_table[i].catch_type);
            )
            out.writeChar(attributes_count);
            for (int i=0; i<attributes_count; i++)
                attributes[i].serialize(out);
        )

)
```

A15. **CONSTANT_Class_info.java**
Convience class for representing CONSTANT_Class_info structures within ClassFiles.

```
import java.lang.*;
import java.io.*;

/** Class subtype of a constant pool entry.   */
public final class CONSTANT_Class_info extends cp_info{

    /** The index to the name of this class. */
    public int name_index = 0;

    /** Convenience constructor.
     */
    public CONSTANT_Class_info(int index) {
        tag = 7;
        name_index = index;
    }

    /** Used during input serialization by ClassFile only. */
    CONSTANT_Class_info(ClassFile cf, DataInputStream in)
        throws IOException{
        super(cf, in);
        if (tag != 7)
            throw new ClassFormatError();
        name_index = in.readChar();
```